Universidade de Aveiro Departamento de Ambiente e Ordenamento
2018

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Respiração do solo *in situ* numa plantação recentemente ardida *versus* não ardida de pinheiro-bravo

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia do Ambiente, realizada sob a orientação científica do Doutor Mário Miguel Azevedo Cerqueira, Professor Auxiliar do Departamento de Ambiente e Ordenamento da Universidade de Aveiro, e a coorientação do Doutor Jan Jacob Keizer, Investigador Principal do Centro de Estudos do Ambiente e do Mar (CESAM) da Universidade de Aveiro e da Doutora Bruna Raquel Figueiredo Oliveira, bolseira de pós-doutoramento do Centro de Estudos do Ambiente e do Mar (CESAM) da Universidade de Aveiro

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o júri

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palavras-chave

Incêndios, florestas mediterrânicas, *Pinus pinaster*, respiração do solo e severidade do incêndio

resumo

Os incêndios florestais são uma das numerosas ameaças que afetam as florestas mediterrânicas, principalmente devido a fatores climáticos, abandono de práticas rurais e práticas inadequadas de manejo florestal. As alterações climáticas também apresentam um papel importante, devido ao aumento da temperatura e diminuição da precipitação. Portugal é um dos países da Europa mais afetados por incêndios florestais. O ano de 2017 foi um dos mais severos desde que existem registos (ano de 1980), com 442 418 hectares de floresta ardida.

Os incêndios florestais têm várias consequências nas propriedades e componentes do solo, especialmente na biomassa abaixo do solo e na matéria orgânica do mesmo. Para entender o modo como os incêndios florestais afetam a dinâmica do carbono, a respiração do solo foi monitorizada numa plantação de pinheiro-bravo durante os primeiros seis meses após o incêndio florestal. A área de estudo queimada, que apresenta uma severidade alta, foi dividida em três unidades estruturais: sob a copa das árvores sem agulhas (UCNN), próximo a um arbusto (S) e uma clareira sem vegetação (IP). Para avaliar o efeito do fogo e da sua severidade na respiração do solo, foi também monitorizada outra unidade estrutural debaixo da copa das árvores numa área com agulha natural presente (UCWN). Além disso, as mesmas unidades estruturais foram monitorizadas num local de controlo que não ardeu nos últimos 10 anos.

De um modo geral, as taxas de respiração do solo foram menores no local queimado em relação ao não queimado, e a unidade estrutural que registou os maiores valores de respiração do solo foi sob a copa das árvores. A presença de agulhas não apresentou efeitos importantes na respiração do solo. A temperatura do solo e a temperatura do ar registaram valores mais altos na área de controlo, enquanto que, para a humidade do solo, ocorreu o oposto.

keywords

Wildfire, Mediterranean forest, *Pinus pinaster*, soil respiration, fire severity

abstract

Wildfires are one of the numerous threats that affect Mediterranean forests, mostly due to climatic factors, abandonment of rural practices and inadequate forest management practices. Climate change has an important role as well due to the increase of temperature and decrease of precipitation. Portugal is one of the most affected countries in Europe by wildfires. The year of 2017 was one of the severest since there are records (the year of 1980) with 442 418 ha of forest burnt.

Wildfires have several consequences on soil properties and components, especially on the below-ground biomass and soil organic matter. In order to understand how wildfires, affect carbon dynamics, soil respiration was monitored on a maritime pine plantation during the first six months after the wildfire. The high severity burnt study area was divided in three structural units: under the canopy of the trees without needle cast (UCNN), near a shrub (S), and interpatch without vegetation (IP). To assess the effect of fire the severity on soil respiration, the soil respiration under the tree canopies was monitored also on an area where natural needle cast (UCWN) was present. In addition, the same structural units were monitored in a control site that didn't burnt in the past 10 years.

In a general way, the soil respiration rates were lower in the burnt site compared to the unburnt, and the structural unit that registered the higher soil respiration values was the UC. The presence of needle cast didn't show major effects on soil respiration Soil temperature and air temperature registered higher values at the UNB site, however for soil moisture the opposite occurred.

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Acronyms

BUR – Burnt forest

C – Carbon

DSR – Daily severity rate

FWI – Fire weather index

GNR – Guarda Nacional Republicana

HWC – Hot water extractable carbon

ICNF – Instituto da Conservação da Natureza e das Florestas

IP – Interpatch

OM – Organic matter

Rs – Soil respiration

S – Shrub

SEPNA – Serviço de Proteção da Natureza e do Ambiente

SM – Soil moisture

UC – Under the canopy

UCNN – Under canopy without needle cast

UCWN – Under canopy with natural needle cast

UNB – Unburnt young stand

µC – Electric conductivity

Chapter 1

General Introduction

1.1 Wildfires in Portugal

Continental Portugal covers an area of 89 000 km^2 (Kanevski and Pereira, 2017). The north and center have an irregular topography, a dense river network and the predominance of forestry and semi natural areas, while the south is characterized by lower altitudes and agricultural areas (Tonini et al., 2017). Portugal mainland climate is influenced by: the position and magnitude of Azores anticyclone, the Mediterranean Sea and North Africa and the moderating effect of the Atlantic Ocean (Parente et al., 2018). In this way, Portugal climate has two basic contrasts: the northern with more irregular topography, higher altitudes, denser river network and more forest vegetation cover influenced by the Atlantic Ocean and the southern with lower altitudes, high aridity and agricultural areas that is influenced by the Mediterranean Sea (Parente et al., 2016; Tavares, 2013).
Forestry occupies approximately one-third of the country (Marques et al., 2011) . According to the Corine Land Cover survey of 2006, of the total area of Portugal mainland 47% is devoted to agriculture and 48% occupied by forests and semi natural areas, which is dominated by shrublands (49%), forest (47%) and open spaces with litter or no vegetation (inter-patches; 4%) (Kanevski and Pereira, 2017). The national forest is mainly occupied by four species: maritime pine (*Pinus pinaster*), eucalypt (*Eucalyptus globulus*), cork oak (*Quercus suber*), and holm oak (*Quercus rotundifolia*) (Moreira et al., 2009).

According to the data released by the Portuguese Institute for Nature and Forest Conservation (ICNF), 2017 was atypical concerning wildfires, with a total of 16 981 fire events which resulted in 442 418 hectares of burnt forest (Figure 1). As referred before, Continental Portugal covers an area of 89 000 km^2 and in the year of 2017 it burnt 4424 km^2, that correspond to 5% of Portugal area.

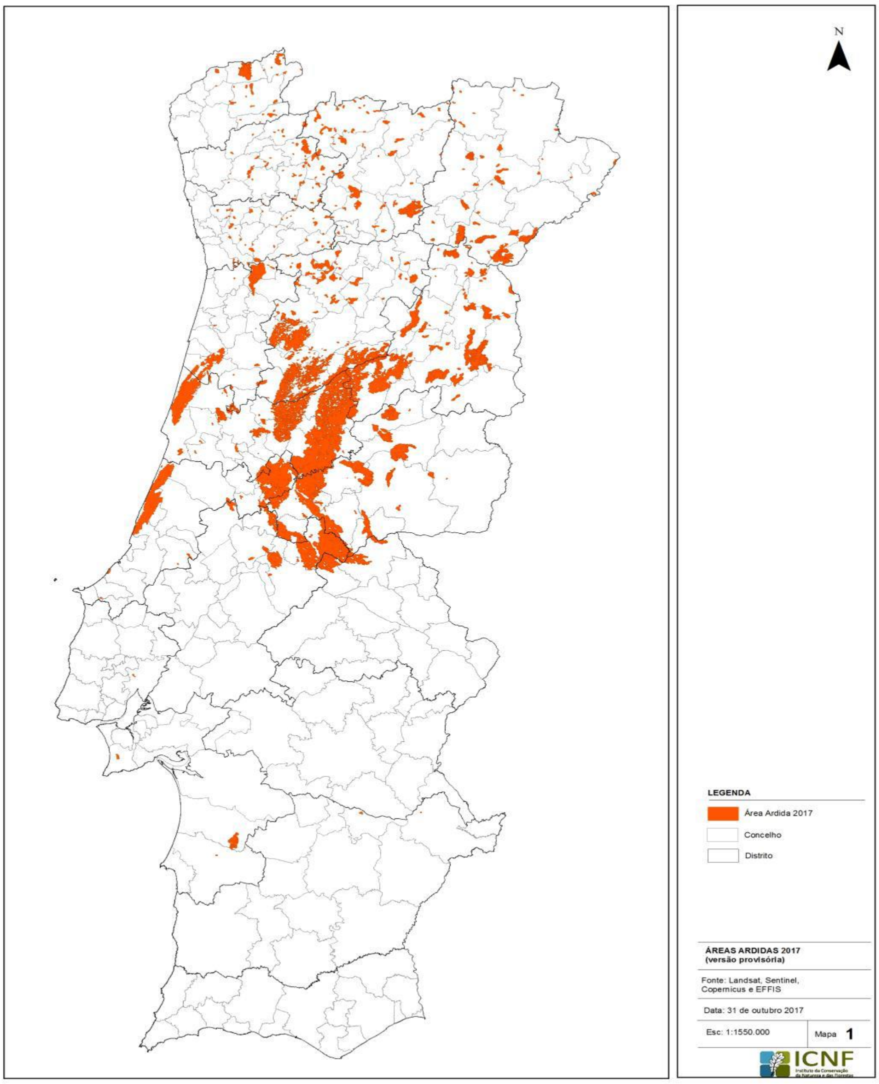

Figure 1: Distribution of burnt areas in Portugal in 2017, until 31th of October (Instituto da Conservação da Natureza e das Florestas, 2017).

In this way, 2017 registered the most extensive burnt area since 1995 (Figure 2). Of the total of fire occurrences, 21% correspond to forest fires. The years of 2003 and 2005 also registered high extension of burnt areas which was associated with weather and drought conditions, such as high temperatures and few precipitation (Fernandes, 2014).

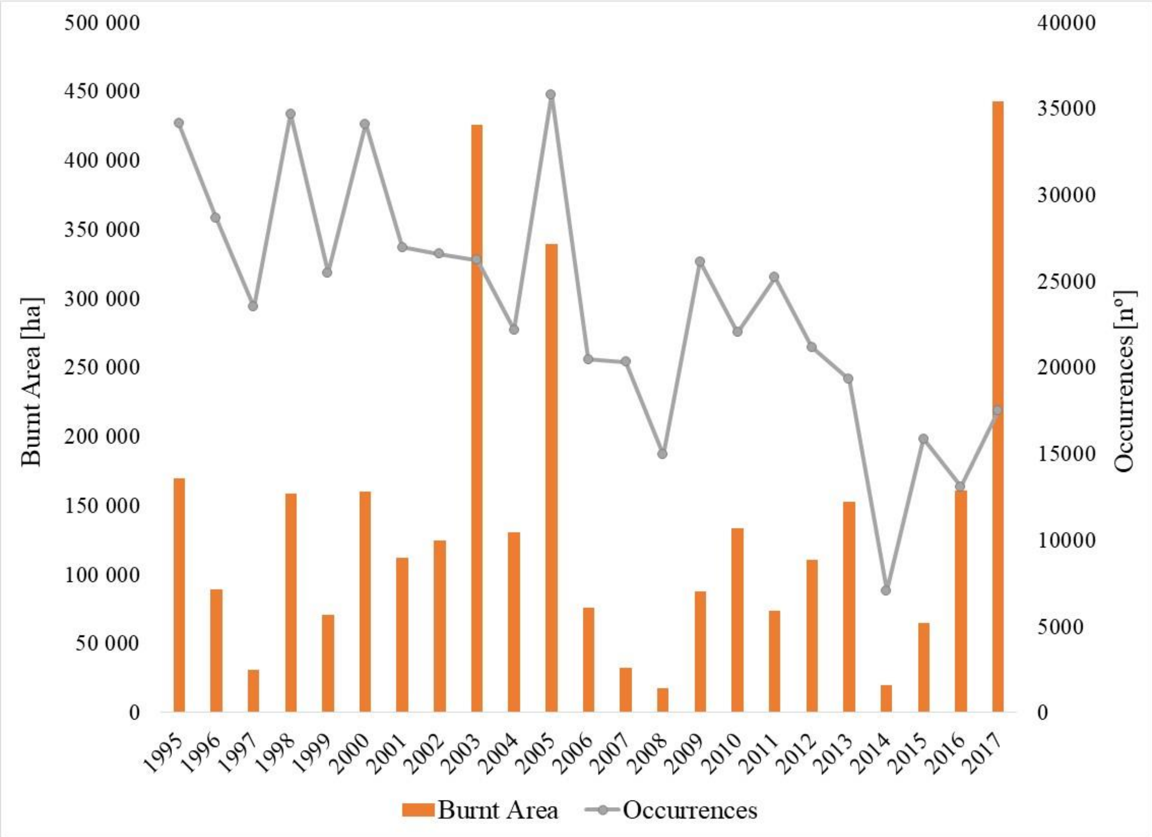

Figure 2: Occurrences and burnt area in continental Portugal between 1995 and 2017 (Fernandes et al., 2018).

The daily severity rating (DSR) allows the assessment of risk of wildfires occurrence, having in account the fire weather index (FWI) that represents the difficulty of controlling the wildfire due to climatic factors (Instituto da Conservação da Natureza e das Florestas, 2017). The DSR shows that the year of 2017 was the most severe of the last 15 years (Instituto da Conservação da Natureza e das Florestas, 2017). The values accumulated begin to stabilize in September, based on historical events, however in 2017 the conditions maintained severe until the beginning of November

In order to understand the reasons that lead to this high number of wildfires, during the year of 2017, the Portuguese Republican National Guard (GNR) through the Portuguese Protection of Nature and Environment Service (SEPNA) investigated 70% of the total of fire events (Fernandes et al., 2018). The investigation shows that 36% of the occurrences have undetermined causes and 23% result from criminal incendiary actions (Figure 3).

23% of the wildfires started from the traditional agricultural practice that encompass the use of fire (Figure 3) to prepare the soil for new crops, acting also as a waste elimination procedure and to promote the growing of grass to be used for cattle feedstock (Gomes, 2006). Therefore, natural, structural and accidental causes represent a very low proportion of the fire events.

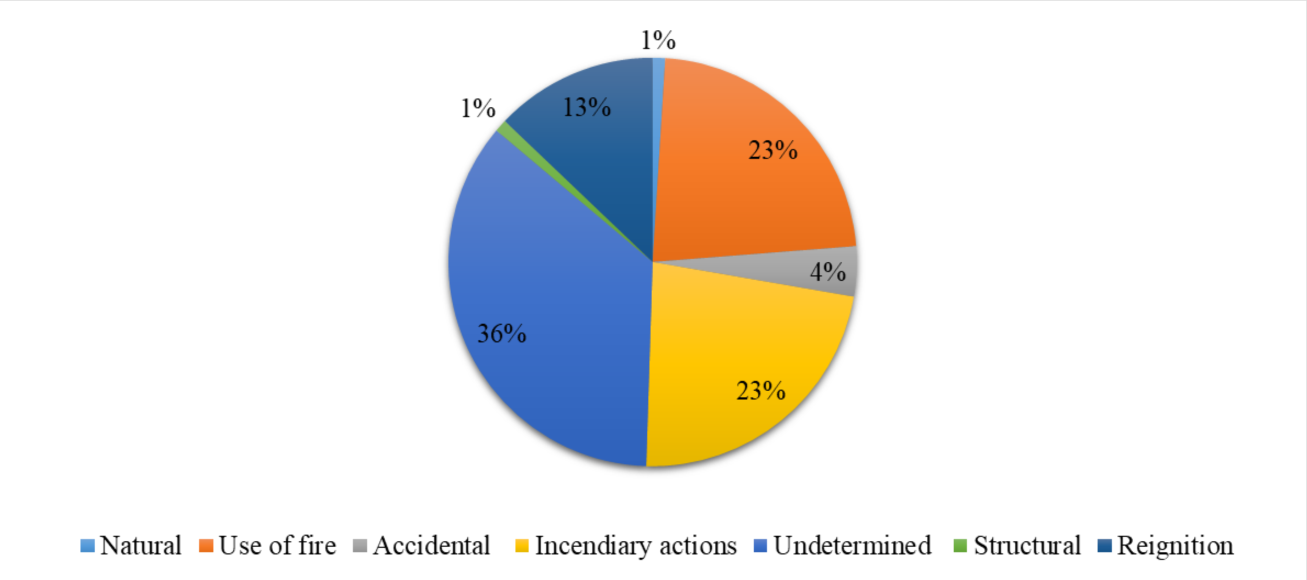

Figure 3: Causes of wildfires of 2017 investigated by GNR/SEPNA (Fernandes et al., 2018).

The number and extension of wildfires has increased over the last decades and constitutes one of the major disturbances on the ecosystems (Bastos et al., 2011). Portugal presents the highest number of burnt area due to wildfires in Europe and it is also the country with the highest number of private forestry. (Silva et al., 2011).

The Portuguese forestry is dominated by fire-prone species, such as maritime pine (*Pinus pinaster*) for wood production and eucalypt (*Eucalyptus globulus*) for paper and pulp mills, which represents approximately 50% of the planted forest in Portugal (Maia et al., 2014).

Inadequate forest management practices, such as the lack of bush and forest residue collection (Pereira et al., 2006), and the increase in temperature and decrease in temperature in the past years (Ferreira-Leite et al., 2017) contribute to the increase of the extension and number of wildfires. All together makes Portugal one of the most fire affected countries in Europe between the years of 1990 and 2017 (Tonini et al., 2017).

1.2 Effects of wildfires on soils and soil respiration

The most important carbon pool in terrestrial ecosystems are forests and an average of 69-75% of this C is found below-ground in the living biomass and soil organic matter (Dixon et al., 1994). Soils store about two-thirds of terrestrial C and soil respiration (R_S) is the second largest contributor to terrestrial-atmosphere carbon fluxes, being gross photosynthesis the first. The soil respiration is the sum of autotrophic respiration from plants metabolic activity and heterotrophic respiration from the decomposition of organic material by microbes (Uribe et al., 2013). Soil respiration is a key indicator of soil health and quality that reflects the level of microbial activity and provides an indication of the ability of soils to support plant growth (Muñoz-Rojas et al., 2016). Degradation of the physical, chemical and/or biological properties of the soils can have major consequences in the quality and quantity of soils leading to the loss of their functions (Lal, 2015). The main soil degradation processes are directly related to erosion, fires, deforestation and pollution (Certini, 2005).

Wildfires, due to the high temperature reached, can have significant impacts through heating and combustion, in the case of the litter layer. There are many soil properties and components affected by wildfires, such as soil organic matter, nutrient availability and soil water repellency (Certini, 2005). The soil organic matter in the uppermost soil layer is charred during a wildfire, which results in profound effects on soil properties, such as soil structure and permeability (Novara et al., 2011). The spatial and temporal effects of wildfires on soils depend mostly on four factors: fire severity, the topography of the burnt area, the vegetation regrowth and post-fire meteorological conditions (Certini, 2005).

Fire severity, according to González-De Vega et al. (2016) can be defined as “the loss of or change in the organic matter aboveground and belowground and has been found to be the most critical factor that directly affects plant responses”. However, assessing the severity of a wildfire can be difficult, because the quantitative characterization of the heating regime (temperature reached and the duration) it is a true challenge (Varela et al., 2015). Low-to-moderate severity fire does not have a considerable impact on soil properties, since the major changes are due to ash production combined with post-fire environmental conditions, local topography and rainfall (Certini, 2005; Francos et al., 2018b).

The ash incorporation into the soil profile causes an increase in soil properties, such as soil aggregate stability, soil organic matter, total carbon and nitrogen, pH and electric conductivity (Francos et al., 2018a), and can lead to a reduction in soil microbial biomass and respiration, due to the increase in soil temperature (Certini, 2005). When the fire has low-to-moderate severity the recovery of the landscape is more rapid since the soil temperature suffers an increase that results of the decreasing albedo (Francos et al., 2018a).

For high severity wildfires the opposite happens, i.e., the entire litter and soil organic matter is consumed, which leads to a decrease in soil organic matter, total carbon and nitrogen, pH and electric conductivity (Francos et al., 2018a). The ashes produced are grey and/or white which indicates the total combustion of organic matter that lead to an increase of inorganic cations in soil (Pereira et al., 2012).

The consequences of wildfires range from the loss of human lives, and infrastructure to the loss of economic value of the plantations, the disruption of the hydrologic cycle, silting up of water lines due to erosion, and flow increase of superficial water lines (Gomes, 2006). Ultimately, wildfires contribute to land degradation and the desertification of large areas (Ferreira-Leite et al., 2016). All this effects, combined with the removal of vegetation and litter cover after burning, leads to soil loss (Badía et al., 2017). These changes on soils are followed by indirect effects, such as reduced infiltration, increased sediment availability for transport, overflow land generation and soil erosion and degradation (Shakesby et al., 2015).

A high fire recurrence in combination with soil degradation can greatly decrease the recovery capacity of energy flow, nutrient cycling and susceptibility to future disturbances influencing indirectly the carbon balance (López-Serrano et al., 2016). This disturbances that indirectly influence the carbon balance leads to an altering in carbon-flux components such as soil respiration (Martínez-García et al., 2017). Wildfires produce changes in soil respiration rates mostly due to the reduction of the vegetation cover and the deposition of an ash layer that leads to a reduction of the albedo effect on the soil surface (Smith et al., 2010). The impacts that wildfires have on soil respiration rates depend on several environmental factors, such as climate and vegetation, fire severity, post-fire meteorological conditions, post-fire forest management, loss and chemical transformation of the soil organic carbon pools (López-Serrano et al., 2016).

There are several studies about soil respiration, the controlling factors and the variability across ecosystems, however there are few about the effects of wildfires on soil respiration rates. The existing studies are mostly in Mediterranean ecosystems and the main focus is the understanding how different post-fire forest treatments will induce a higher forest recovery. Nevertheless, these studies allowed to get some information about the effects of wildfires, fire severity and the factors that control post-fire soil respiration rates. According to several studies the soil respiration rates are lower at the burnt areas compared with the unburnt (López-Serrano et al., 2016; Martínez-García et al., 2017; Uribe et al., 2013). The three reasons that may explain the decrease of soil respiration after a wildfire are: loss of root respiration and/or the lack of production of labile root exudates due to the plant death, changes in soil organic carbon and the decrease in microbial populations following a fire event (Uribe et al., 2013). According to Martínez-Garcia et al. (2017), the soil respiration rates are lower at high severity areas compared to low-severity which can be explained by the lack of litterfall from the canopy and the progressive decomposition rate, since in the high severity sites the amount of litter resistant to the fire is smaller and the loss of respiration due to plant dead and the reduced microbial community.

In order to understand fire impacts on soil respiration, some studies resort to prescribe fires, however those only reach low severity and the results does not correspond to a wildfire situation. Some authors suggest that soil respiration is higher at burnt than unburnt sites ((López-Serrano et al., 2016; Martínez-García et al., 2017; Uribe et al., 2013)), while others suggest that fire does not affect soil respiration, such as Plaza-Álvarez et al. (2017). The soil respiration rates similar at burnt and unburnt areas, can be explained by the fact that soil microbiota and soil root systems were not affected by the low temperatures and residence time.

1.3 Aims and thesis structure

The main goal of this thesis is understanding the effects of wildfires on soil respiration in Maritime pine plantations as one of the most widespread and most fire-prone tree species in Portugal.

The specific objectives of this study were to assess:

1) the indirect effects of fire occurrence and severity on *in situ* soil respiration;
2) the spatial variability in soil respiration rates, particularly the role therein of the structural units of pine trees; the dominant shrub species and inter-patches;
3) the evolution of soil respiration with time-since-fire during the first six post-fire months and the role therein of antecedent weather and soil moisture conditions.

The thesis is divided in two chapters:

- Chapter 1 gives an introduction to background information about wildfires in Portugal and their environmental impacts and, in particular, soils, providing the motivation for this thesis;
- Chapter 2 presents the findings of this MSc thesis study in the format of an article for an international scientific journal and, as such, is divided in introduction, materials and methods, results and discussion, and conclusions.

References

Badía, D., López-García, S., Martí, C., Ortíz-Perpiñá, O., Girona-García, A., Casanova-Gascón, J., 2017. Burn effects on soil properties associated to heat transfer under contrasting moisture content. Sci. Total Environ. 601–602, 1119–1128. https://doi.org/10.1016/j.scitotenv.2017.05.254

Bastos, A., Gouveia, C.M., Dacamara, C.C., Trigo, R.M., 2011. Modelling post-fire vegetation recovery in Portugal. Biogeosciences 8, 3593–3607. https://doi.org/10.5194/bg-8-3593-2011

Certini, G., 2005. Effects of fire on properties of forest soils: A review. Oecologia 143, 1–10. https://doi.org/10.1007/s00442-004-1788-8

Dixon, A.R.K., Brown, S., Houghton, R.A., Solomon, A.M., Trexler, M.C., 1994. Carbon Pools and Flux of Global Forest Ecosystems Published by : American Association for the Advancement of Science Stable URL : http://www.jstor.org/stable/2882371 263, 185–190.

Fernandes, A.C., Ribeiro, R., Rodrigues, S., Fernandes, A.C., 2018. Relatório do Estado do Ambiente - Portugal 2018.

Fernandes, P., 2014. Forest Context and Policies in Portugal 19. https://doi.org/10.1007/978-3-319-08455-8

Ferreira-Leite, F., Bento-Gonçalves, A., Vieira, A., Nunes, A., Lourenço, L., 2016. Incidence and recurrence of large forest fires in mainland Portugal. Nat. Hazards 84, 1035–1053. https://doi.org/10.1007/s11069-016-2474-y

Ferreira-Leite, F., Ganho, N., Bento-Gonçalves, A., Botelho, F., 2017. Iberian atmosferic dynamics and large forest fires in mainland Portugal. Agric. For. Meteorol. 247, 551–559. https://doi.org/10.1016/j.agrformet.2017.08.033

Francos, M., Pereira, P., Mataix-Solera, J., Arcenegui, V., Alcañiz, M., Úbeda, X., 2018a. How clear-cutting affects fire severity and soil properties in a Mediterranean ecosystem. J. Environ. Manage. 206, 625–632. https://doi.org/10.1016/j.jenvman.2017.11.011

Francos, M., Úbeda, X., Pereira, P., Alcañiz, M., 2018b. Long-term impact of wildfire on soils exposed to different fire severities. A case study in Cadiretes Massif (NE Iberian Peninsula). Sci. Total Environ. 615, 664–671. https://doi.org/10.1016/j.scitotenv.2017.09.311

Gomes, J.F.P., 2006. Forest fires in Portugal: How they happen and why they happen. Int. J. Environ. Stud. 63, 109–119. https://doi.org/10.1080/00207230500435304

González-De Vega, S., De las Heras, J., Moya, D., 2016. Resilience of Mediterranean terrestrial ecosystems and fire severity in semiarid areas: Responses of Aleppo pine forests in the short, mid and long term. Sci. Total Environ. 573, 1171–1177. https://doi.org/10.1016/j.scitotenv.2016.03.115

Instituto da Conservação da Natureza e das Florestas, 2017. Relatório Provisório de Incêndios Florestais – 2017.

Kanevski, M., Pereira, M.G., 2017. Local fractality: The case of forest fires in Portugal. Phys. A Stat. Mech. its Appl. 479, 400–410. https://doi.org/10.1016/j.physa.2017.02.086

Lal, R., 2015. Restoring soil quality to mitigate soil degradation. Sustain. 7, 5875–5895. https://doi.org/10.3390/su7055875

López-Serrano, F.R., Rubio, E., Dadi, T., Moya, D., Andrés-Abellán, M., García-Morote, F.A., Miettinen, H., Martínez-García, E., 2016. Influences of recovery from wildfire and thinning on soil respiration of a Mediterranean mixed forest. Sci. Total Environ. 573, 1217–1231. https://doi.org/10.1016/j.scitotenv.2016.03.242

Maia, P., Keizer, J., Vasques, A., Abrantes, N., Roxo, L., Fernandes, P., Ferreira, A., Moreira, F., 2014. Post-fire plant diversity and abundance in pine and eucalypt stands in Portugal: Effects of biogeography, topography, forest type and post-fire management. For. Ecol. Manage. 334, 154–162. https://doi.org/10.1016/j.foreco.2014.08.030

Marques, S., Borges, J.G., Garcia-Gonzalo, J., Moreira, F., Carreiras, J.M.B., Oliveira, M.M., Cantarinha, A., Botequim, B., Pereira, J.M.C., 2011. Characterization of wildfires in Portugal. Eur. J. For. Res. 130, 775–784. https://doi.org/10.1007/s10342-010-0470-4

Martínez-García, E., López-Serrano, F.R., Dadi, T., García-Morote, F.A., Andrés-Abellán, M., Pumpanen, J., Rubio, E., 2017. Medium-term dynamics of soil respiration in a Mediterranean mountain ecosystem: The effects of burn severity, post-fire burnt-wood management, and slope-aspect. Agric. For. Meteorol. 233, 195–208. https://doi.org/10.1016/j.agrformet.2016.11.192

Moreira, F., Vaz, P., Catry, F., Silva, J.S., 2009. Regional variations in wildfire susceptibility of land-cover types in Portugal: Implications for landscape management to minimize fire hazard. Int. J. Wildl. Fire 18, 563–574. https://doi.org/10.1071/WF07098

Muñoz-Rojas, M., Lewandrowski, W., Erickson, T.E., Dixon, K.W., Merritt, D.J., 2016. Soil respiration dynamics in fire affected semi-arid ecosystems: Effects of vegetation type and environmental factors. Sci. Total Environ. 572, 1385–1394. https://doi.org/10.1016/j.scitotenv.2016.02.086

Novara, A., Cerda, A., Gristina, L., Bodi, M.B., 2011. the Impact of Fire on Redistribution of Soil Organic Matter on a. L. Degrad. Dev. 22, 530–536.

Parente, J., Pereira, M.G., Amraoui, M., Fischer, E.M., 2018. Heat waves in Portugal: Current regime, changes in future climate and impacts on extreme wildfires. Sci. Total Environ. 631–632, 534–549. https://doi.org/10.1016/j.scitotenv.2018.03.044

Parente, J., Pereira, M.G., Tonini, M., 2016. Space-time clustering analysis of wildfires: The influence of dataset characteristics, fire prevention policy decisions, weather and climate. Sci. Total Environ. 559, 151–165. https://doi.org/10.1016/j.scitotenv.2016.03.129

Pereira, J.M.C., Carreiras, J.M.B., Silva, J.M.N., Vasconcelos, M.J., 2006. Alguns Conceitos Básicos sobre os Fogos Rurais em Portugal, in: Pereira, J.., Pereira, J.M.., Rego, F.., Silva, J.M.., Silva, T.. (Eds.), Incêndios Florestais Em Portugal: Caracterização, Impactes e Prevenção. ISAPress.

Pereira, P., Úbeda, X., Martin, D.A., 2012. Fire severity effects on ash chemical composition and water-extractable elements. Geoderma 191, 105–114. https://doi.org/10.1016/j.geoderma.2012.02.005

Plaza-Álvarez, P.A., Lucas-Borja, M.E., Sagra, J., Moya, D., Fontúrbel, T., Heras, J., 2017. Soil Respiration Changes after Prescribed Fires in Spanish Black Pine (Pinus nigra Arn . ssp . salzmannii) Monospecific and Mixed Forest Stands 3–5. https://doi.org/10.3390/f8070248

Shakesby, R.A., Bento, C.P.M., Ferreira, C.S.S., Ferreira, A.J.D., Stoof, C.R., Urbanek, E., Walsh, R.P.D., 2015. Impacts of prescribed fire on soil loss and soil quality: An assessment based on an experimentally-burned catchment in central Portugal. Catena 128, 278–293. https://doi.org/10.1016/j.catena.2013.03.012

Silva, J.S., Vaz, P., Moreira, F., Catry, F., Rego, F.C., 2011. Wildfires as a major driver of landscape dynamics in three fire-prone areas of Portugal. Landsc. Urban Plan. 101, 349–358. https://doi.org/10.1016/j.landurbplan.2011.03.001

Smith, D.R., Kaduk, J.D., Balzter, H., Wooster, M.J., Mottram, G.N., Hartley, G., Lynham, T.J., Studens, J., Curry, J., Stocks, B.J., 2010. Soil surface CO2flux increases with successional time in a fire scar chronosequence of Canadian boreal jack pine forest. Biogeosciences 7, 1375–1381. https://doi.org/10.5194/bg-7-1375-2010

Tavares, B.M., 2013. Alterações climáticas e consumo energético em edifícios sustentáveis. Universidade de Aveiro.

Tonini, M., Pereira, M.G., Parente, J., Vega Orozco, C., 2017. Evolution of forest fires in Portugal: from spatio-temporal point events to smoothed density maps. Nat. Hazards 85, 1489–1510. https://doi.org/10.1007/s11069-016-2637-x

Uribe, C., Inclán, R., Sánchez, D.M., Clavero, M.A., Fernández, A.M., Morante, R., Cardeña, A., Blanco, A., Van Miegroet, H., 2013. Effect of wildfires on soil respiration in three typical Mediterranean forest ecosystems in Madrid, Spain. Plant Soil 369, 403–420. https://doi.org/10.1007/s11104-012-1576-x

Varela, M.E., Benito, E., Keizer, J.J., 2015. Influence of wildfire severity on soil physical degradation in two pine forest stands of NW Spain. Catena 133, 342–348. https://doi.org/10.1016/j.catena.2015.06.004

Chapter 2

Article

2.1 Introduction

Forests store 69-75% of the terrestrial C and soil respiration (R_S) is the second largest contributor to terrestrial-atmosphere carbon fluxes, being gross photosynthesis the first. Soil respiration is the sum of autotrophic respiration from plants metabolic activity and heterotrophic respiration from the decomposition of organic material by microbes (Uribe et al., 2013). Soil respiration is a key indicator of soil health and quality that reflects the level of microbial activity and provides an indication of the ability of soils to support plant growth (Muñoz-Rojas et al., 2016).

Wildfires are part of the dynamics of the planet Earth and are recognized as a natural phenomenon in Mediterranean countries, playing an important role in the evolution of the ecosystems (Ferreira-Leite et al., 2016). However, wildfires can have significant impacts on the carbon balance of ecosystems by directly releasing carbon (C) into the atmosphere via vegetation, litter and soil organic matter combustion as well as by altering carbon-flux components such as soil respiration (Martínez-García et al., 2017). The increase in intensity, severity and frequency of wildfires in the Mediterranean region, in combination with soil degradation, can decrease the recovery capacity of fire-prone ecosystems in terms of energy flow, nutrient cycling and susceptibility to future disturbances, influencing indirectly the carbon balance (López-Serrano et al., 2016; Certini et al., 2011; Uribe et al., 2013).

Wildfires impact soil respiration rates through the reduction of vegetation cover and the decrease of the albedo effect on the soil surface due to the presence of a dark ash layer, which increases soil temperature and decomposition rates (Smith et al., 2010). The impacts of wildfires on soil respiration rates and the magnitude of these impacts will depend on several environmental factors such as climate and vegetation, fire severity, post-fire meteorological conditions, post-fire forest management, loss and chemical transformation of the soil organic carbon pools (López-Serrano et al., 2016). The combination of the factors mentioned, often lead to a higher resistance to chemical and biological degradation, an increase in the ability of the vegetation to recovery, alteration in fine root dynamics and soil conditions and changes in the autotrophic and heterotrophic respiration (Uribe et al., 2013).

Soil respiration is mainly controlled by temperature, precipitation, soil moisture, soil organic matter quantity and quality, root and microbial biomass, root nitrogen content, soil acidity and soil texture (Curiel et al., 2003). Even though soil respiration is an important contributor to the global C cycle, there is a limited understanding of the variability across ecosystems and the controlling factors (Morillas et al., 2017).

There are several studies about the effects of post-fire treatments (López-Serrano et al., 2016; Martínez-García et al., 2017; Uribe et al., 2013) but not on the evolution of soil respiration with time-since-fire.

Therefore, the specific objectives of this study were to determine: (i) the indirect effects of fire occurrence and severity on *in situ* soil respiration; (ii) the spatial variability in soil respiration rates, particularly the role therein of the structural units of pine trees; the dominant shrub species and inter-patches; (iii) the evolution of soil respiration with time-since-fire during the first six post-fire months and the role therein of antecedent weather and soil moisture conditions.

2.2 Material and Methods

2.2.1 Study area and sites

The study area is a maritime pine plantation in Central Portugal that was burnt by a wildfire on August 13th of 2017, that affected 10 282 ha. This area has a Csa temperate Mediterranean climate in the Köppen-Geiger Climate Classification system, with dry and temperate summers with cold nights and moderate drought (CLIMATE-DATA, 2018). To complement the research, an unburnt (UNB) control area, with similar tree age and soil type, was selected as close as possible to the burnt area (BUR). The geographical distance between both study areas is approximately 1 km. The burnt study area was divided in four structural units: under the canopy whit no needle cast (UCNN); interpatch without vegetation (IP); as close as possible to the remain twigs of *Chamaespartium tridentatum* shrubs (S); and under the canopy with natural needle cast (UCWN). UCNN, IP and S are in a high severity burnt area while the UCWN is in a moderate severity burnt area. The unburnt area was divided in three structural units: UC, IP and S.

The trees species found in those sites are 95% *Pinus pinaster* (maritime pine) with 8 to 10 years, 2% *Eucalyptus globulus* and 3% *Arbutus unedo*. The UNB site has a slope of 5% and the BUR site does not have a slope.

2.2.2 Meteorological conditions

A meteorological station was set up at both study sites, providing 15 minutes recordings of air temperature (Figure 4) and relative humidity (Figure 5). In the BUR site, the meteorological station, was placed in an interpatch and at the UNB site was located in the middle of the trees, both stations at a height of 2 meters.

In addition, two tipping-bucket rainfall gauges (Pronamic Professional Rain Gauge with 0.2 mm resolution) and two storage gauges (in-house design) were installed in the BUR and UNB sites (Figure 6).

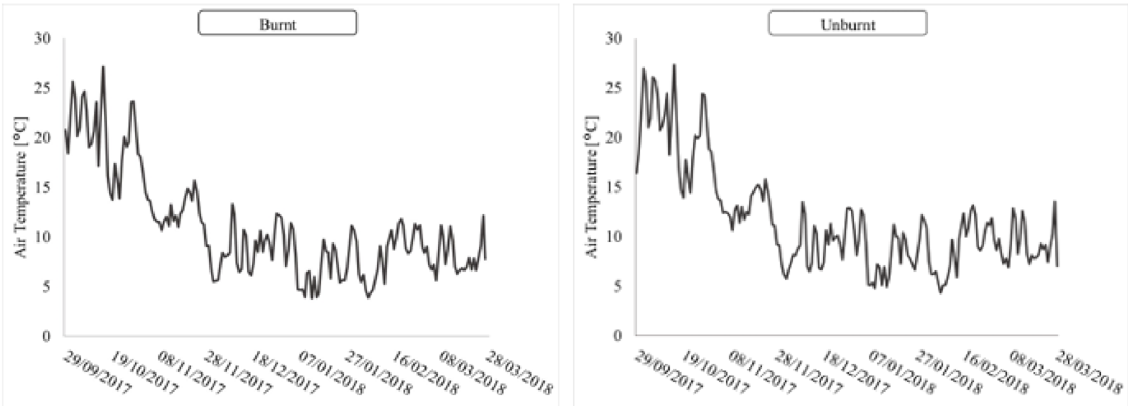

Figure 4: Daily mean values of air temperature for the burnt and unburnt sites.

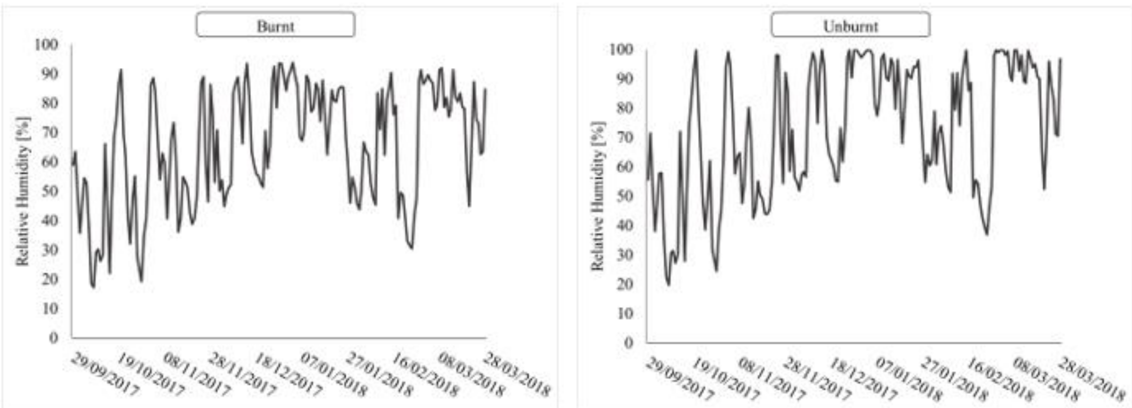

Figure 5: Daily mean values of relative humidity for the burnt and unburnt sites.

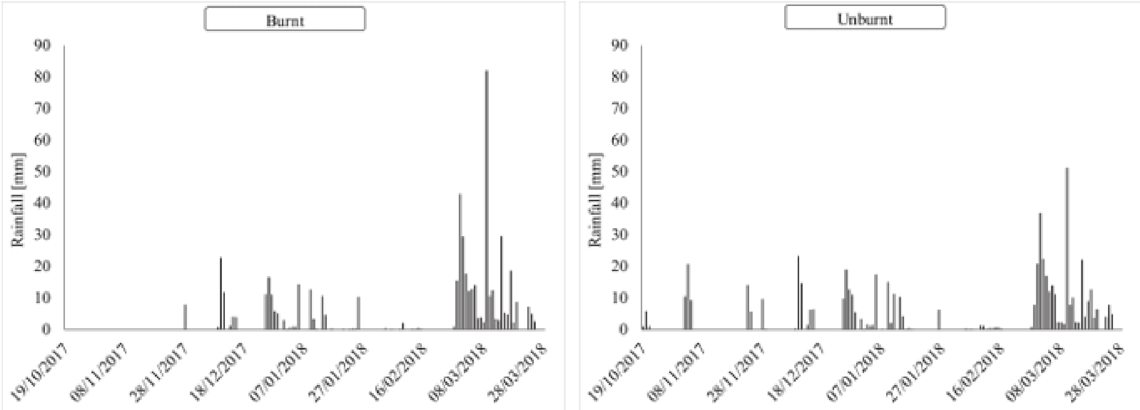

Figure 6: Daily mean values of rainfall for the burnt and unburnt sites.

2.2.3 Soil properties and moisture conditions

Soil sampling was done to evaluate the differences in organic matter (OM, %), pH, electric conductivity (µC) and hot-water extractable carbon (HWC, mg C g^{-1} soil), between the BUR and UNB sites. The samples were collected from each of the structural units at both BUR and UNB sites. The soil sampling was done on September 9th of 2017 and the soil samples were taken at two depths: 0-2 centimeters and 2-7 centimeters. In addition, the ashes were sample in the BUR site. The soil samples were sieved at 2mm and stored at 4 °C before analysis.

Ash and soil organic matter content were determined according with the ASTM D 2974-87 Standard Test Methods for Moisture, Ash, and Organic Matter of Peat and Other Organic Soils. Soil pH was determined following the ISO 10390:2005, while soil electrical conductivity (µC) was determined following the ISO 11265:1994. The water-soluble carbon (WSC) and the hot-water extractable carbon (HWEC) were determined following the method described in Ghani et al., (2003) Total carbon in the WSC and HWEC extracts was determined on a Shimadzu total organic carbon (TOC) analyzer model 5000A.

The soil organic matter content (Figure 7) was higher in the 0-2 centimeters layer than in the 2-7 centimeters layer at the burnt and unburnt site. The average values of OM, at both depths, was higher at the unburnt than the burnt sites (17% *versus* 7%). The lower values of OM after the fire can be explained by the high severity occurred, due to the high temperatures reached in combustion (Francos et al., 2018a; Mikita-Barbato et al., 2015). Those high temperatures lead to the loss of humus and litter layer that causes a decrease of the soil organic matter (Jiménez-González et al., 2016). Also, the organic matter concentrates on the surface of the soil and for that reason it is particularly destructed by fires, which leads to major losses. (Zavala et al., 2014)

The average values of OM content of the ashes (24%) is higher than at 0-2 centimeters (15%) and 2-7 centimeters (9%). This values suggest an incomplete vegetation combustion that lead to an increase of the organic matter (Campos et al., 2016).

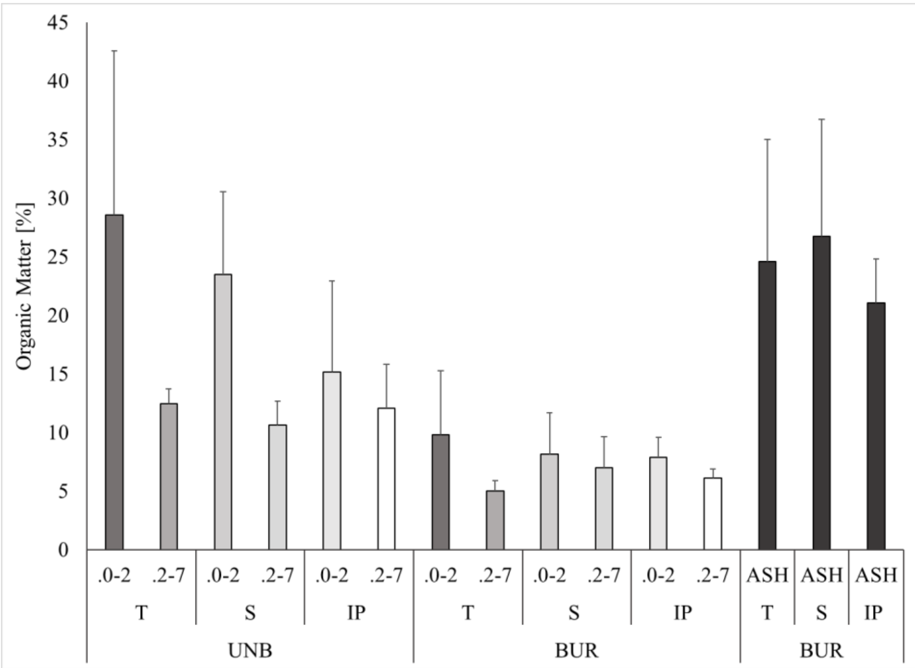

Figure 7: Organic matter for the burnt and unburnt site at different depths.

The pH values (Figure 8) for the unburnt and burnt site range from 4 and to 5, for the several structural units at both depths. For the burnt site, at the depth of 0-2 and 2-7 centimeters, the values are very similar to the ones registered for the unburnt site. Other authors had recorded the same, for example Badía et al., (2017), concluded that pH wasn't significantly affected by burning, like other properties (organic matter, soil moisture content, water repellency, color, organic C, total N and total dissolved solutes). No major differences were recorded between the depth of 0-2 and 2-7 centimeters, but also between the three structural units, since the values are very similar at both sites.

Regarding the ashes, for the burnt site, the pH values are much higher than for the three structural units. It is possible to observe that the structural unit shrub presents the higher value, followed by the under canopy and finally the interpatch. The higher values registered in ashes compared to the other depths can be explained by the contribution of exchangeable cations from the ash (Shakesby et al., 2015). Also, the rise of pH values is due to OH-losses, the complete oxidation of organic matter during the fire and the fire temperature/severity that increases fire ash alkalinity (Alcañiz et al., 2018; Pereira et al., 2012). Another important factor, is that the increase of pH values is inversely related to the decrease in soil organic matter (Francos et al., 2018a), corroborated by this study results.

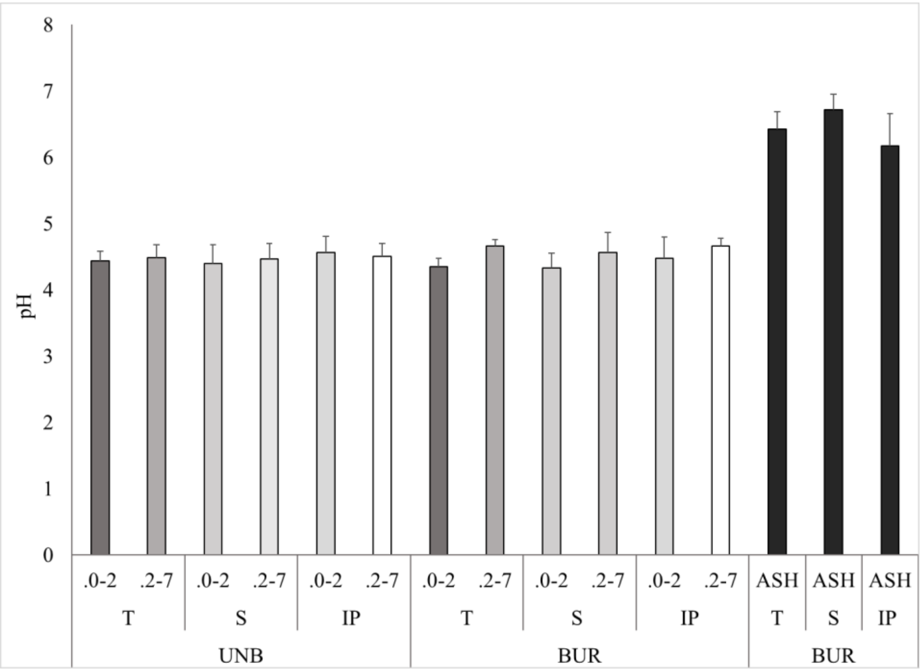

Figure 8: pH for the burnt and unburnt site at different depths.

Regarding the electric conductivity (Figure 9), the values are slightly higher in the burnt site, however without significant differences compared to the unburnt site. This higher values is owing to the release of soluble ions and major cations during the combustion of soil organic matter (Alcañiz et al., 2018). The changes in µC weren't significant and that can be explained by the fact that salts are quickly leached or transported (Zavala et al., 2014).

At the burnt site, the ashes present a significantly higher values of electric conductivity values, the structural unit under canopy presents the higher value followed by the shrub and interpatch. The higher values registered on the ashes of the burnt site are mainly attributed to the release of large quantities of inorganic ions (cations), oxides, hydroxides and carbonates in soils and the high amounts of mineralized nutrients on ashes (Campos et al., 2016).

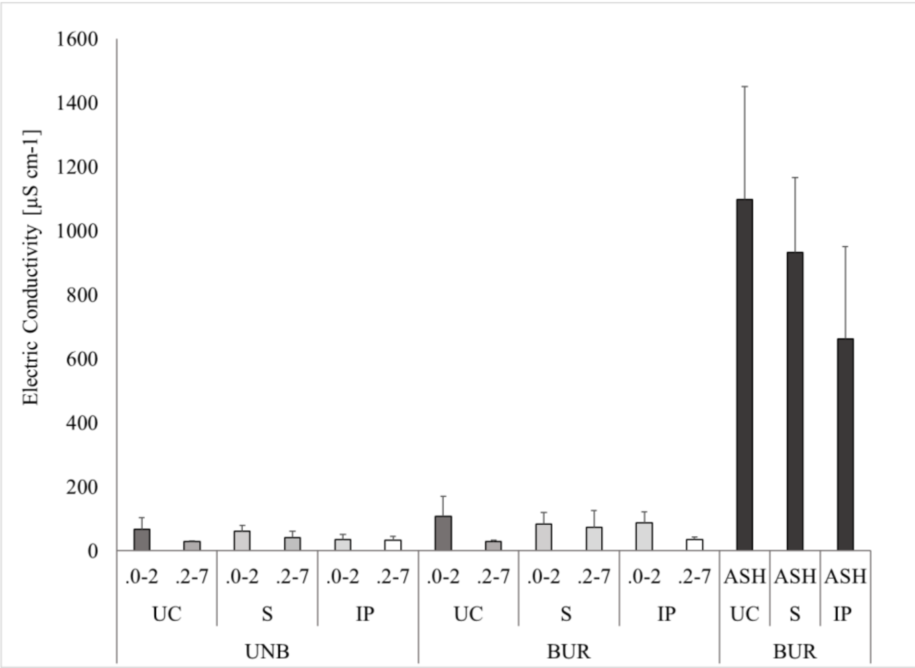

Figure 9: Electric conductivity for the burnt and unburnt site at different depths.

The Hot-water extractable carbon (Figure 10) exhibits slightly higher values for the unburnt site compared to the burnt site, for all structural units at 0-2 centimeters, 2-7 centimeters depths. The significant losses of soil organic matter, already demonstrated, lead to a decrease of organic carbon values (Martín et al., 2012). In this way and knowing that the soil organic matter did not register lower values for ashes, the organic carbon values remain similar to the ones registered at the unburnt site. Through the analysis of the HWC concentration graphic and the soil organic matter it is possible to observe that in the structural units where the losses of OM were higher the losses of organic C were too. The losses of soil organic carbon registered are consistent with previous recorded results (Paré et al., 2011; Poirier et al., 2014; Treseder et al., 2012).

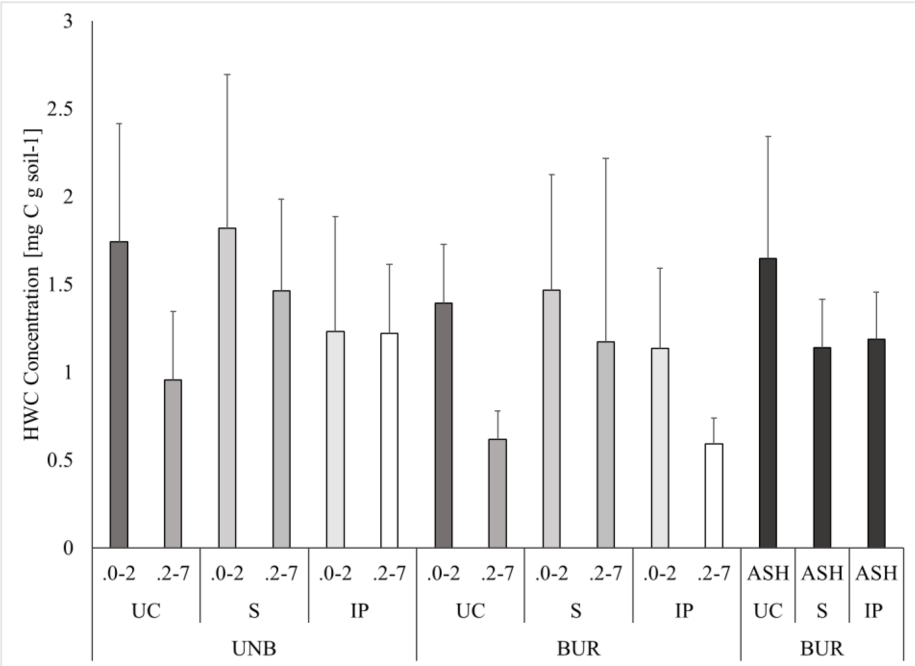

Figure 10: Hot water extractable carbon for the burnt and unburnt site at different depths.

2.2.4 Soil respiration

To assess the evolution of the *in situ* soil respiration with time-since-fire, the BUR and UNB areas were divided in five equidistant points where soil collars were inserted. The soil collars allow the measurement of soil respiration always at the exact same location. Examples of pictures of these structural units can be seen in Figure 11.

Figure 11: Examples of collars placed at the structural units: a) UCNN; b) Interpatch; c) Shrub and d) UCWN.

A transect laid out across each site and at five equidistant points collars were placed next to the nearest pine tree, *Chamaespartium tridentatum,* shrub and inter-patch. In September 2017 in total, 35 PVC collars with 12 cm high and 20 cm of internal diameter, were installed, 20 at the burnt site and 15 at the unburnt site. Soil respiration was measured from September 2017 to March 2018, with a frequency of one sampling per week. The total soil CO_2 efflux can be monitored trough robust and consolidated methods, such as static or dynamic chamber systems equipped with infrared gas analyzers (Matteucci et al., 2015). In this study, the *in situ* soil respiration was measured using an automated soil gas flux system (LI-8100A, LI-COR, Environmental Division, Lincoln, NE, USA) with a survey portable chamber with 20 cm of diameter (Figure 13). These measurements were taken together with soil temperature and moisture reading using a 6000-09TC Soil Probe Thermocouple and a 8100-205 GS1 Soil Moisture Probe sensor, respectively.

Close to each collar, soil temperature and soil moisture were monitored continuously and recorded at 15 minutes intervals using Decagon GS3 and EC5 sensors, respectively. For soil moisture, the sensors were placed at a depth of: 2,5 cm near the tree; 2,5 cm near the shrub; 2,5 cm and 7,5 cm in the interpatch. Regarding soil temperature, the sensors were placed at a depth of: 2,5 cm; 5 cm; 7,5 cm; 10 cm and 20 cm in the interpatch.

Figure 12: Automated soil gas flux system (LI-8100A, LI-COR) with a 20-cm survey portable chamber.

2.3 Results and discussion

2.3.1 Effects of fire occurrence and severity on *in situ* soil respiration rates

The effects of fire occurrence are presented in Figure 13 for the UC structural unit, Figure 14 for IP, and Figure 15 for S. For the three structural units the soil respiration was higher in the UNB site compared to the BUR site. The UNB site registered the maximum value of 4.91 µmol m^{-2} s^{-1} and the BUR 3.68 µmol m^{-2} s^{-1}, for the UC structural unit. That is in accordance with several other studies about Mediterranean forests (López-Serrano et al., 2016; Uribe et al., 2013) that show that the UNB site registered higher values of soil respiration. Although these studies represent other type of treatments and structural units, it was registered higher values for the unburnt sites. This tendency for the BUR sites to show lower Rs values can be explained by the loss of root respiration and/or the lack of production of labile root exudates due to the plant death, also due to changes in soil organic carbon, and due to the decrease in microbial populations following the fire (Uribe et al., 2013). The microbial populations contribute to heterotrophic respiration and soil respiration is the sum of autotrophic respiration and heterotrophic respiration. If the heterotrophic respiration decreases, consequently, the total soil respiration suffers a decrease as well.

The Figures show a peak in soil respiration on 19th of October of 2017.This peak is observed after the first rain event after the wildfire. The rain event induced an increase in soil respiration from 2.46 to 4.91 µmol m^{-2} s^{-1} in the UNB and from 0.91 to 4.12 µmol m^{-2} s^{-1} in the BUR site, for the UC unit. This can be explained by a condonation of three factors: the rapid decomposition of microbial biomass during drought and an increase in surface area of palatable organic substrates the displacement of CO_2-rich air trapped in soil pores; (Marañón-Jiménez et al., 2011). After this peak soil respiration values returned to previous values, which indicates that soil moisture has a significant influence on soil respiration. This high peak followed by a decrease of Rs values, has been reported by other studies, for example Marañón-Jiménez et al. (2011). The study explains that CO_2 it is trapped in soil pores and when the soil is very dry and exists low connectivity with soil pores that leads to an accumulation of CO_2. In this way, when it rains the soil suffers an initial degassing, which explains the peak values registered and the decrease afterwards.

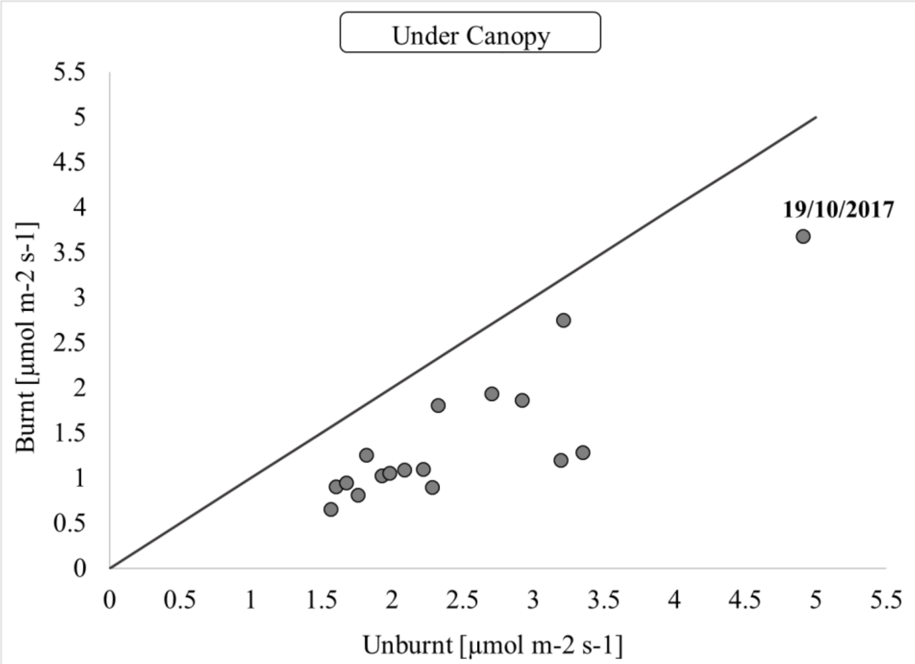

Figure 13: Soil respiration unburnt *versus* burnt for Under Canopy.

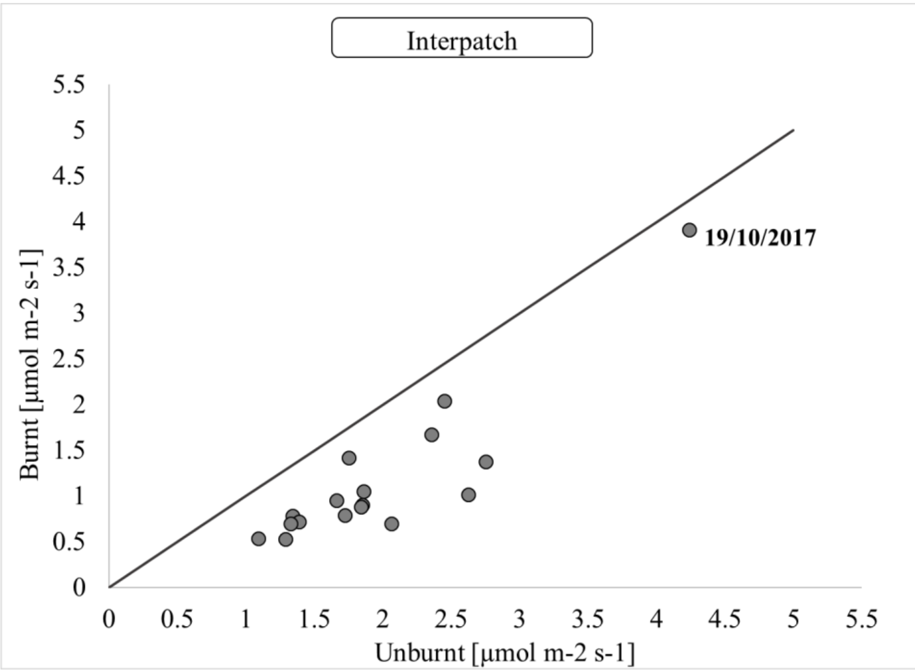

Figure 14: Soil respiration unburnt *versus* burnt for Interpatch.

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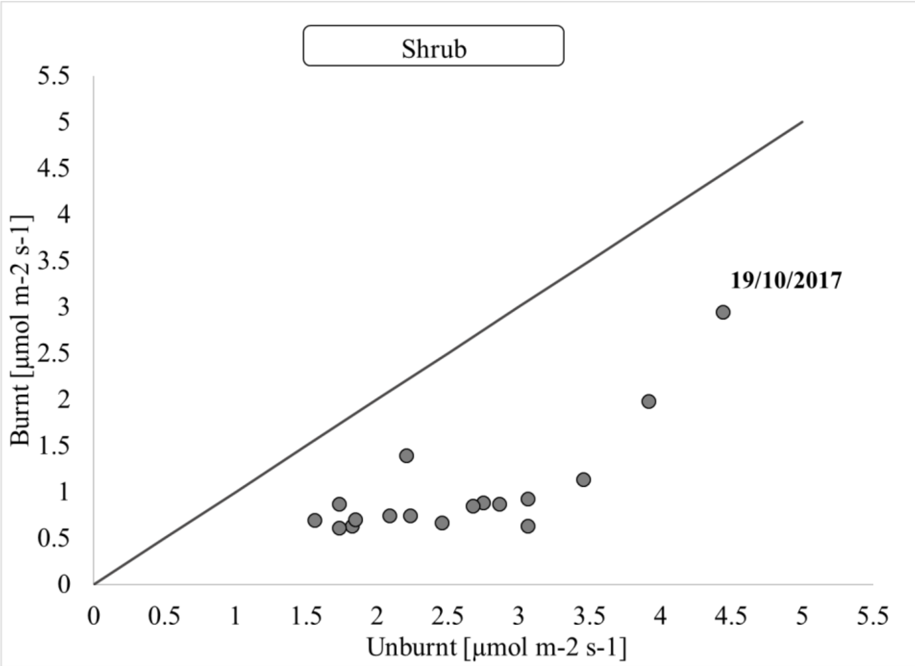

Figure 15: Soil respiration unburnt *versus* burnt for Shrub.

Figure 16 shows the soil respiration of the structural unit UC for high severity (UCNN) and moderate severity (UCWN). The soil respiration on the moderate severity site is slightly higher compared to the high severity. The maximum value registered for moderate severity was 4.12 µmol m^{-2} s^{-1} and for high severity was 3.68 µmol m^{-2} s^{-1}. The lower values registered in high severity can be explained by the lack of litterfall from the canopy and the progressive decomposition rate, since in the high severity sites the amount of litter resistant to the fire is smaller and the loss of respiration due to plant dead and the reduced microbial community (Martínez-García et al., 2017).

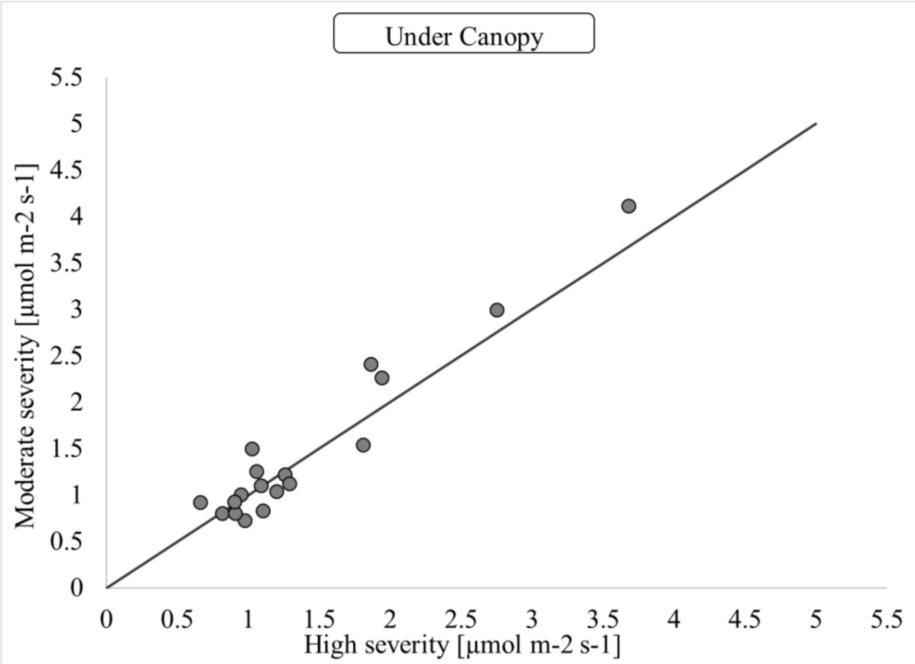

Figure 16: Soil respiration high severity *versus* moderate severity for Under Canopy.

2.3.2 Effects of spatial variability on *in situ* soil respiration rates

Figures 17 to 22 show the effects of spatial variability on soil respiration. For the BUR site (Figures 17 to 19), it is possible to observe that the soil respiration is similar for all structural units, except on 6th and 19th of October of 2017. The difference observed on October 19th is related with the first rain event after the fire while October 6th was the day with highest air (24.13°C, Figure 4) and soil temperature (26.4°C) of the study period. The UNB has similar soil respiration in all structural units, except on 19th of October of 2017. The structural units that presented a strong correlation coefficient were: under canopy moderate severity with under canopy high severity (r = 0.9717); under canopy moderate severity with interpatch burnt (r = 0.9370) and under canopy high severity with interpatch burnt (r = 0.9638). The shrub burnt and shrub unburnt showed a good correlation coefficient (r = 0.7740) and all the other combinations presented a weak correlation coefficient (r < 0.22).

The soil respiration rates present higher values for the under canopy structural unit. For the shrub and interpatch the values are similar, however the shrub registered slightly higher values. For example, at the UNB site, the highest value reached by the interpatch was 4.24 µmol m^{-2} s^{-1}, while in the shrub and under canopy was 4.44 µmol m^{-2} s^{-1} and 4.91 µmol m^{-2} s^{-1}, respectively. The higher Rs values on the under canopy structural unit might be explained by an improved soil microclimate, which means a higher soil temperature and moisture retention (Marañón-Jiménez et al., 2011). Also, a higher wood-soil contact that leads to an increase of the decomposition process and the decaying of litter and woody debris that promotes a higher nutrient supply to the soil (Martínez-García et al., 2017). The fact that the structural unit interpatch presents the lower values of Rs is a consequence of the loss of root respiration due to plant death and a reduced microbial community (Martínez-García et al., 2017). It may also reflect changes in the quantity and quality of soil organic carbon like in other post fire studies (López-Serrano et al., 2016; Marañón-Jiménez et al., 2011; Uribe et al., 2013).

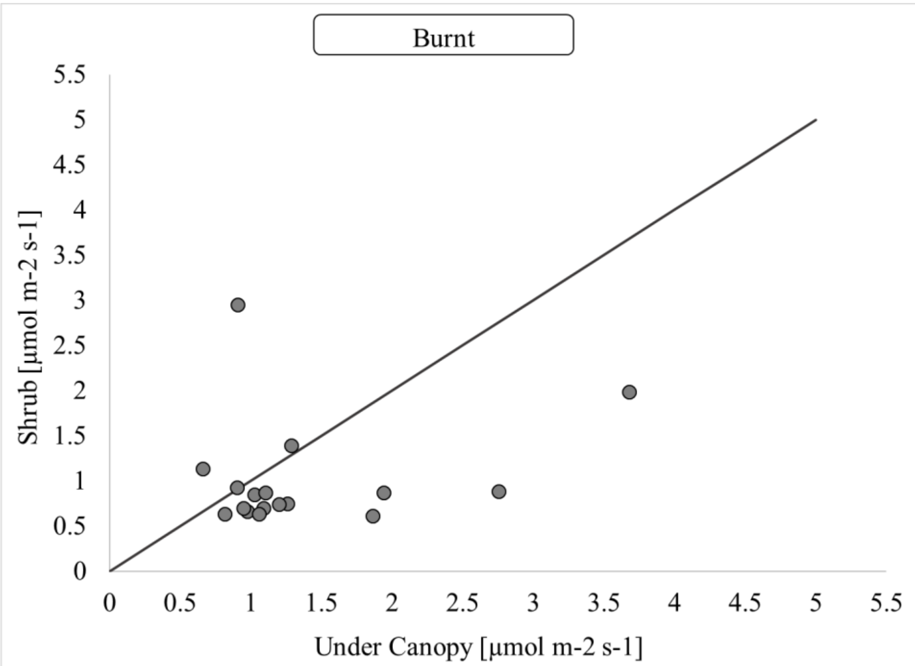

Figure 17: Soil respiration under canopy *versus* shrub for the burnt site.

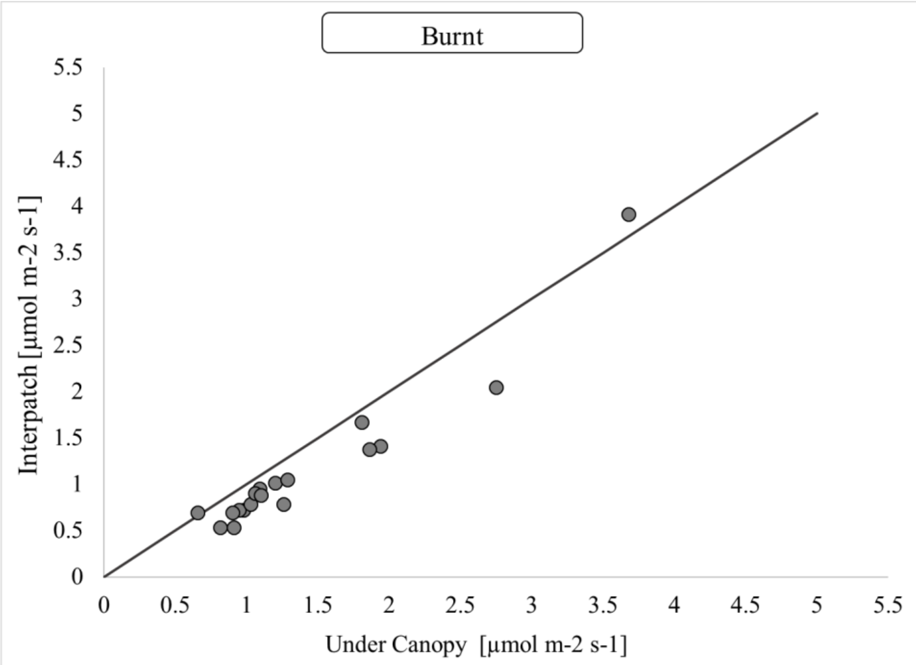

Figure 18: Soil respiration under canopy *versus* interpatch for the burnt site.

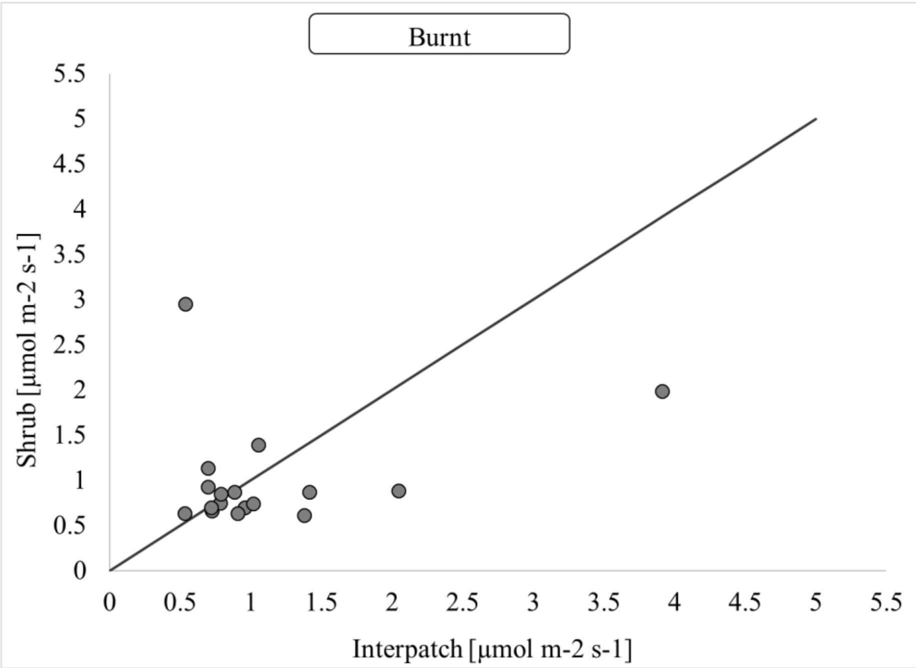

Figure 19: Soil respiration shrub *versus* interpatch for the burnt site.

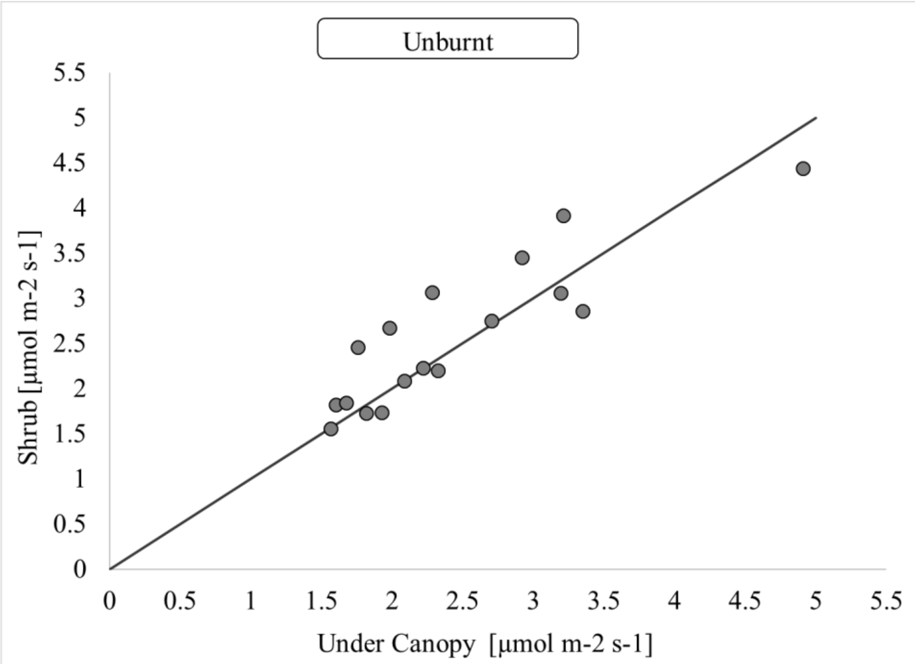

Figure 20: Soil respiration under canopy *versus* shrub for the unburnt site.

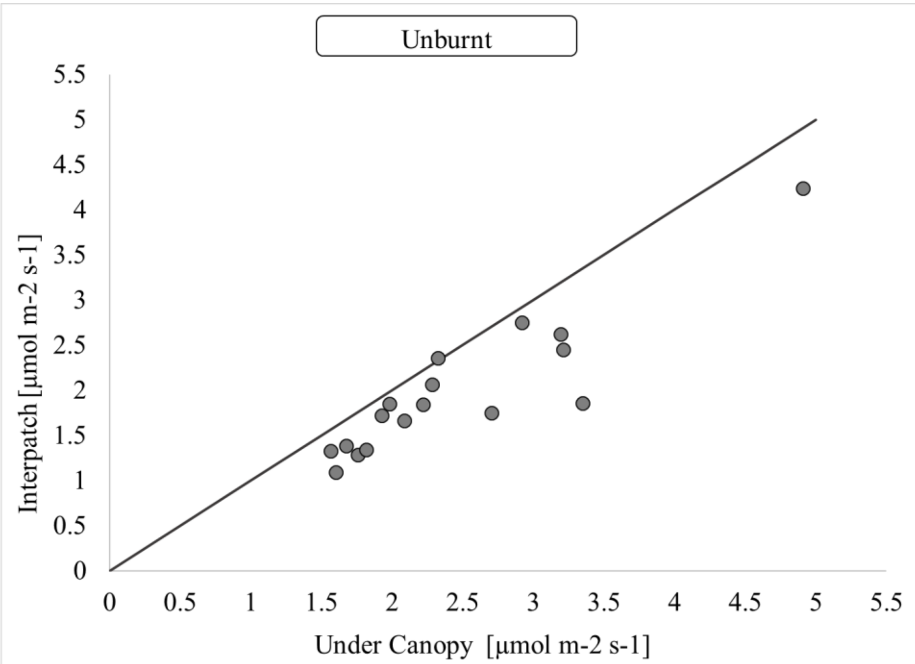

Figure 21: Soil respiration under canopy *versus* interpatch for the unburnt site.

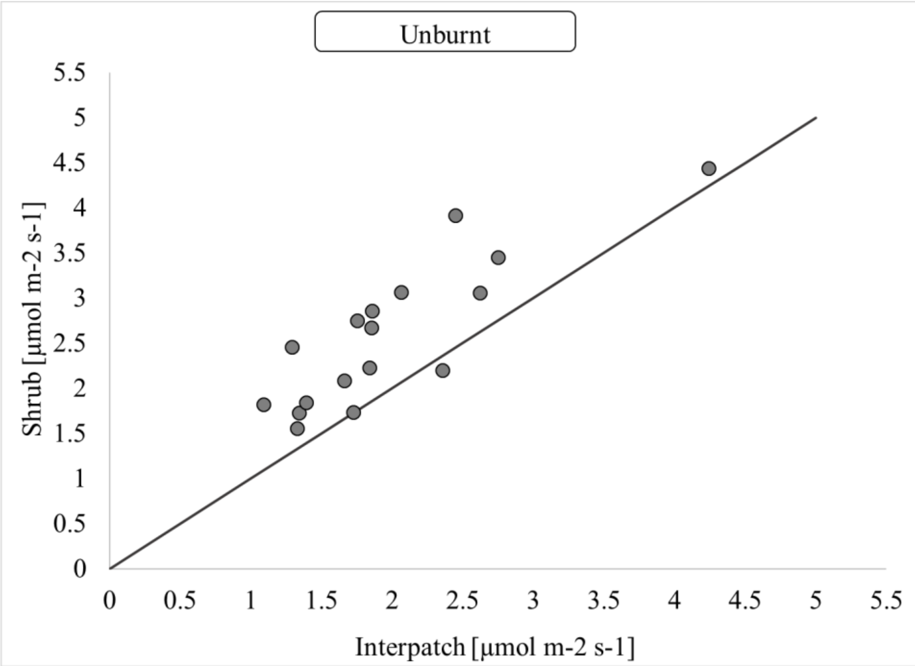

Figure 22: Soil respiration interpatch *versus* shrub for the unburnt site.

2.3.3 Evolution of soil respiration rates with time since fire

The evolution of soil respiration rates with time since fire is represented in Figure 23 for Under Canopy unit, Figure 24 for Interpatch unit and Figure 25 for the Shrub unit.

The Figures show that throughout the entire measurement period the Rs values were higher for the UNB site compared to the BUR, for the UC structural unit. This situation has been reported in other studies in forest ecosystems, where after a wildfire the Rs rates suffer a reduction and that even after many years the BUR sites show lower values of soil respiration (Uribe et al., 2013). However, there are some studies where the opposite was found, *i.e.* the Rs rates were higher in the BUR site compared to the UNB six months after the fire (Muñoz-Rojas et al., 2016). This higher Rs rates can be explained by the fire restrain on autotrophic Rs in short term due to root mortality, although this effect can be shrouded by the increase in heterotrophic Rs (Muñoz-Rojas et al., 2016). Microbial biomass and activity usually recover much faster than vegetation after fire (Muñoz-Rojas et al., 2016). Nevertheless, according to the results obtained in this study, neither the microbial biomass or vegetation recovered to the point of increasing Rs rates.

Also, the evolution of the Rs values is similar in the BUR and UNB sites since whenever there is a peak or a decrease that behavior. On 28th of March of 2018, the Rs values for BUR and UNB were becoming closer to each other, which could indicate that some recovery is starting. In fact, at the BUR site, is already possible to observe some vegetation growing. The increase of C pool is directly related with the increasing time since fire (Köster et al., 2016) and the formation of new organic matter. It can take from 3 to 10 years for the ecosystem to recover to the state before the fire event (Köster et al., 2016).

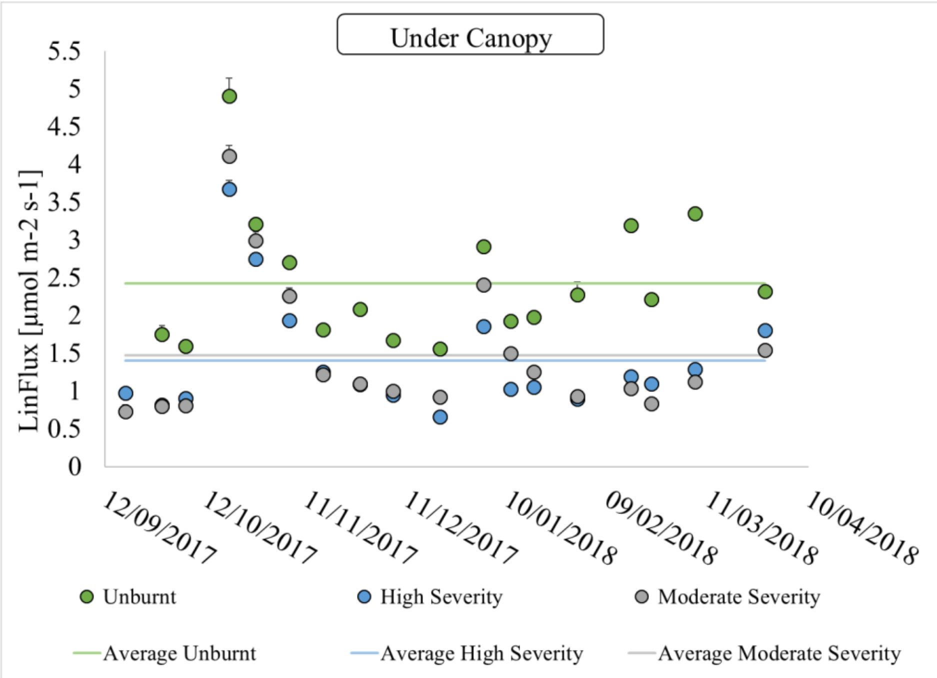

Figure 23: Soil respiration with time since fire for Under Canopy.

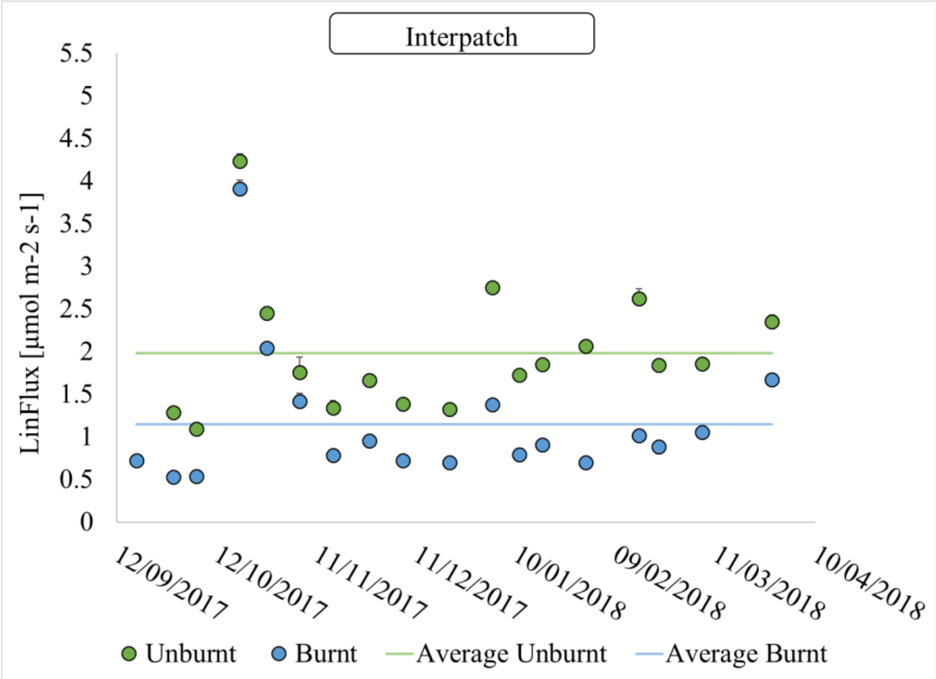

Figure 24: Soil respiration with time since fire for Interpatch.

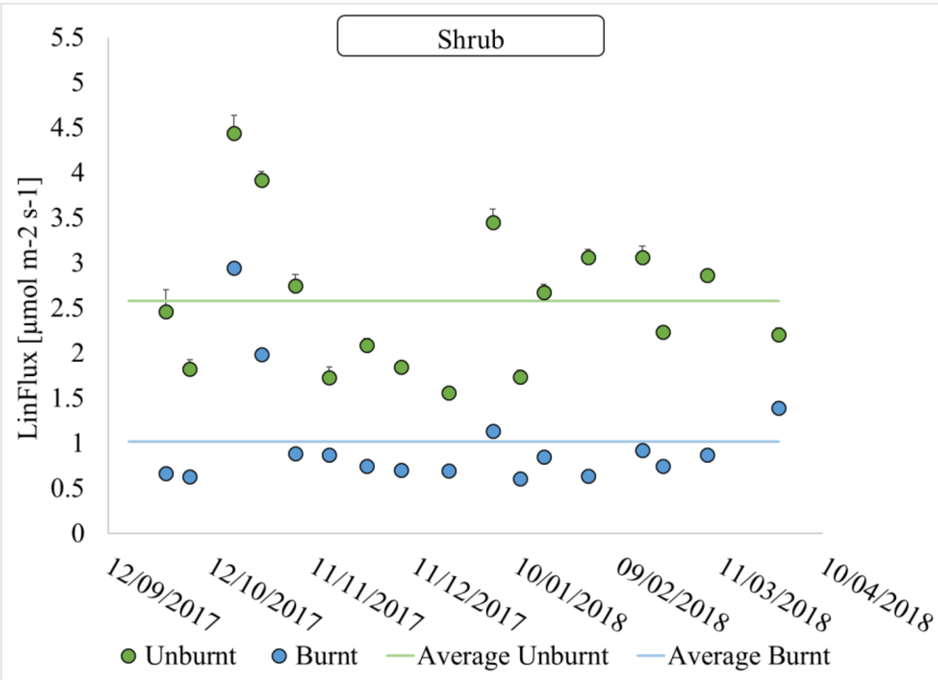

Figure 25: Soil respiration with time since fire for Shrub.

2.3.4 Effects of soil conditions and weather on *in situ* soil respiration rates

The soils conditions and weather parameters analyzed are: soil temperature, soil moisture and air temperature. The effects of soil temperature are represented in the following graphics, that show the relation between the values of soil respiration and the daily average of soil temperature on the three structural units: under canopy, shrub and interpatch, for the BUR (Figure 26) and UNB site (Figure 27). Through the analysis of the graphics regarding the BUR site, it is possible to observe that most of the values are very similar, apart from four values that deviate from the main pattern. Those four values correspond to the measurements performed at: 29th of September of 2017, 6th, 19th and 27th of October. As explained previously, the 19th of October is related with the first rain event, that lead to a peak in Rs rates. The measurements of 29th of September of 2017 and of 6th of October of 2017, correspond to days with high values of soil temperature registered and low values of soil moisture. However, the Rs rates did not increase, because although the soil temperature was higher, the soil moisture was low due to the fact that only rained at 19th of October of 2017.

Lastly, high values of soil temperature and soil moisture were registered in 27th of October of 2017, since it had already rained and the Rs values increased. This can be explained by the fact that higher values of soil temperature lead to greater soil surface evaporation but to lower evapotranspiration, so soil moisture increases and Rs rates increase (Martínez-García et al., 2017). For the UNB site graphics the pattern was the same, having four values that deviate from it that correspond to the same days of measurements. Comparing the values of soil temperature between the site, the BUR registered higher values. The maximum value registered at the BUR site was 27°C and for the UNB site was 20°C. That can be explained by the fact that the soil surface is more exposed to direct soil radiation since occurred a reduction in canopy shading (López-Serrano et al., 2016; Martínez-García et al., 2017)

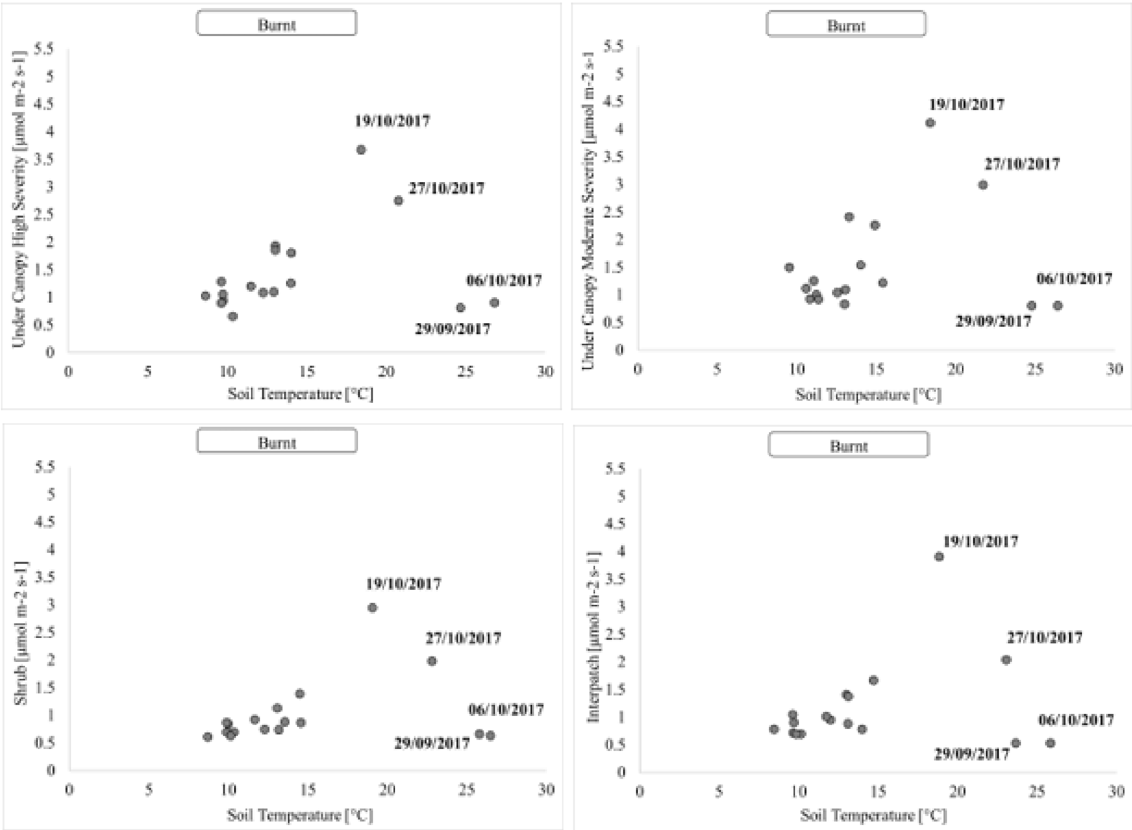

Figure 26: Soil respiration *versus* soil temperature for the burnt site.

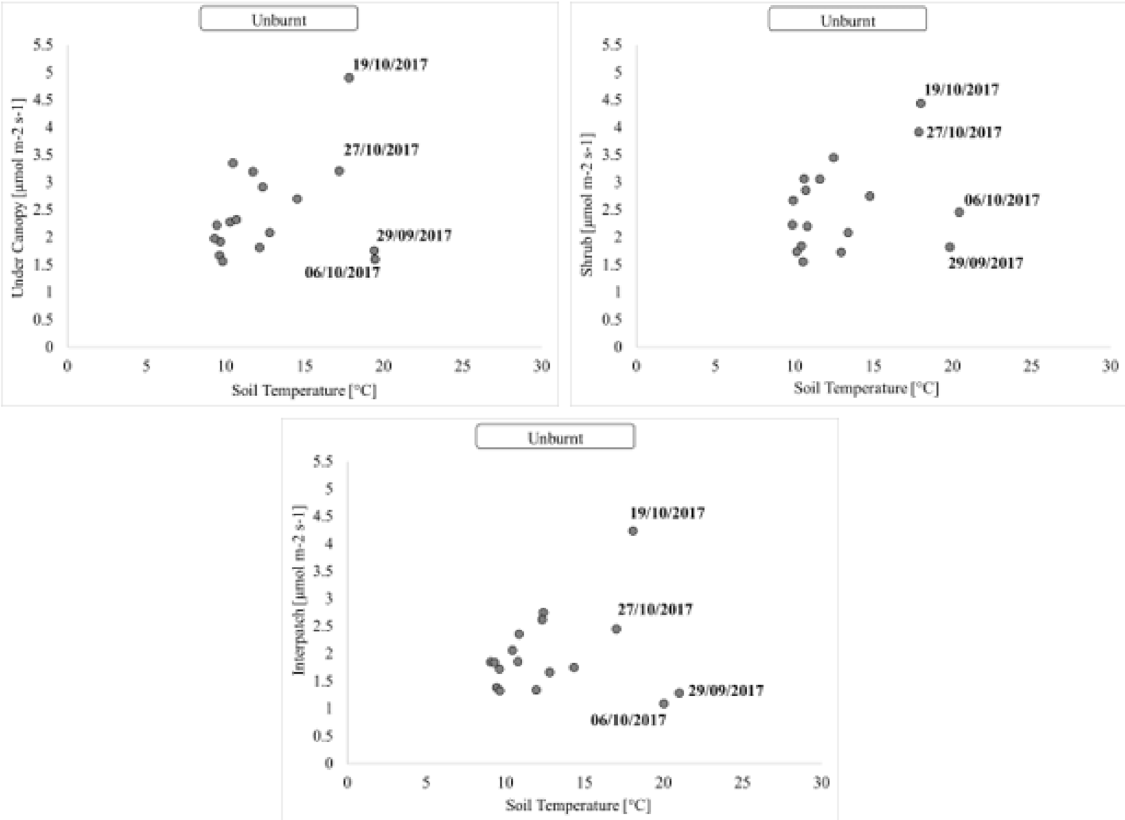

Figure 27: Soil respiration *versus* soil temperature for the unburnt site.

The effects of soil moisture are represented in the following graphics, that show the relation between the values of soil respiration and the daily average of soil moisture on the three structural units: under canopy, shrub and interpatch, for the BUR (Figure 28) and UNB site (Figure 29). For the BUR site, the soil moisture values registered were moderate, not going beyond 0.2 m^3 m^{-3}, except for moderate severity of the structural unit under canopy. For moderate severity, the values of soil moisture registered stand between 0.2 and 0.8 m^3 m^{-3}, which are much higher than the values of the other structural units. This can be explained by the fact that the needle cast contributes to the retention of water that decrease soil temperature and increase soil moisture, since the soil surface evaporation is lower (Uribe et al., 2013).

In a general way, the BUR site registered slightly lower values of soil moisture compared to the UNB site, except for the under canopy moderate severity. This could be due to a greater soil surface evaporation associated with the increased soil temperature, than can be explained by the reducing of canopy shading caused by the fire (Uribe et al., 2013). Another factor that contributes to the reduction of soil moisture is an increase of water uptake by the post-fire coppiced shrubs and new resprouts (López-Serrano et al., 2016).

For the structural unit interpatch soil moisture was measure at two different depths: 2.5 cm and 7.5 cm, with the objective of understanding the effects of soil moisture on Rs rates at different depths. However, the values registered were very similar and show the same pattern.

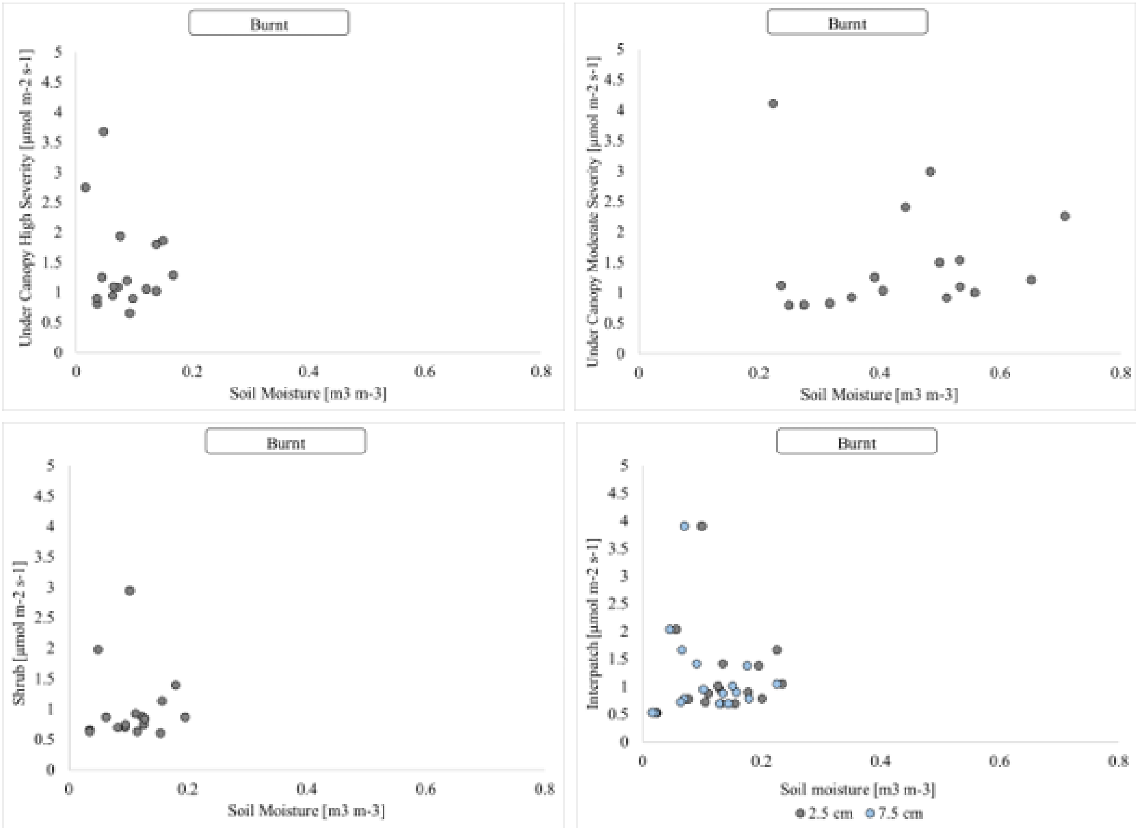

Figure 28: Soil respiration *versus* soil moisture for the burnt site.

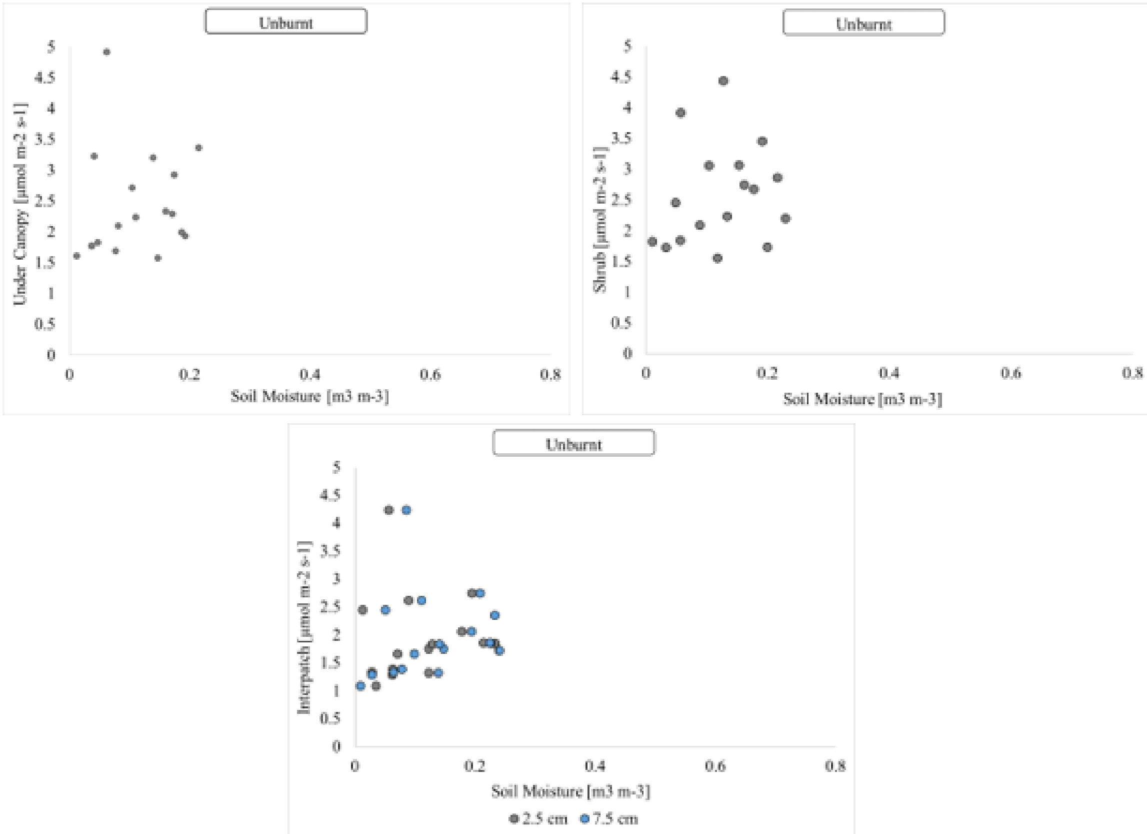

Figure 29: Soil respiration *versus* soil moisture for the unburnt site.

The effects of air temperature are represented in the following graphics, that show the relation between the values of soil respiration and the daily average of air temperature on the three structural units: under canopy, shrub and interpatch, for the BUR (Figure 30) and UNB site (Figure 31). The analysis of the graphics for both sites allow to verify that, as expressed in soil temperature and soil moisture graphics, there are a main pattern and four values that deviate from that. These values, as explained before, correspond to measurements performed at 29th of September of 2017, 6th, 19th and 27th of October. In this way, air temperature graphics verify the variations in Rs rates, since in the days that soil temperature registered higher values, air temperature also registered.

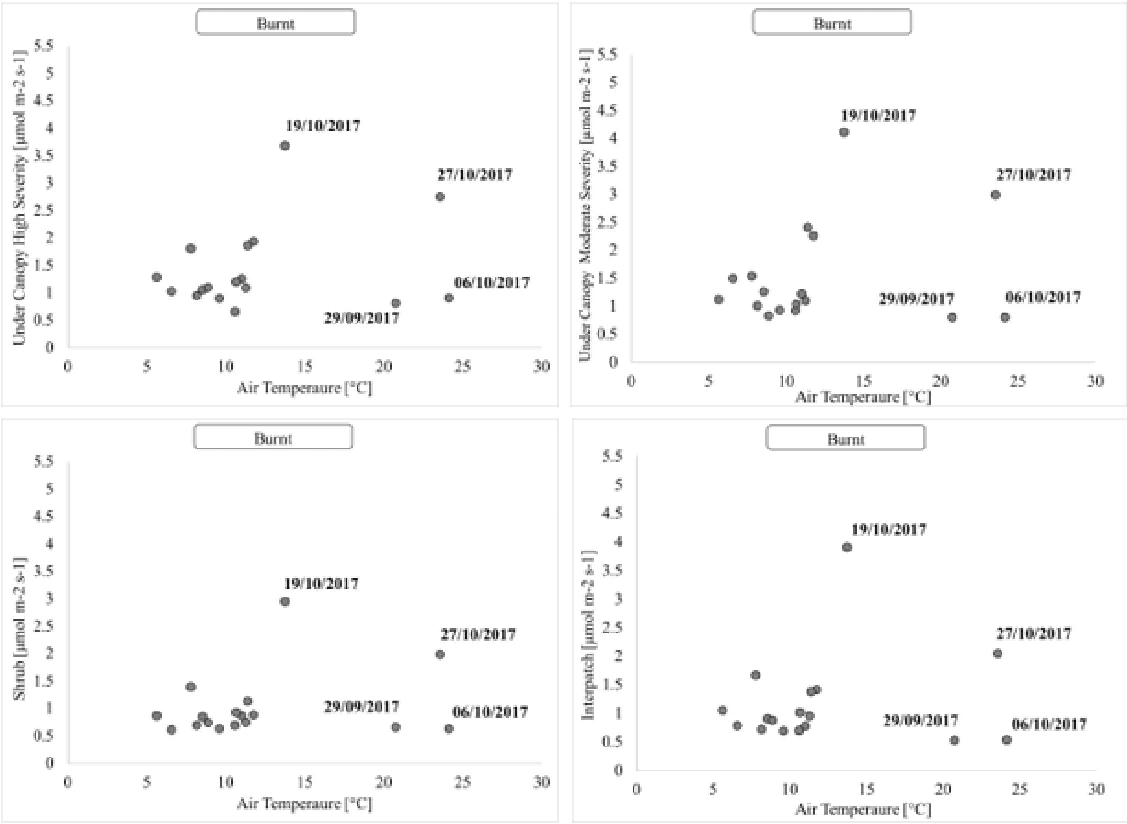

Figure 30: Soil respiration *versus* air temperature for the burnt site.

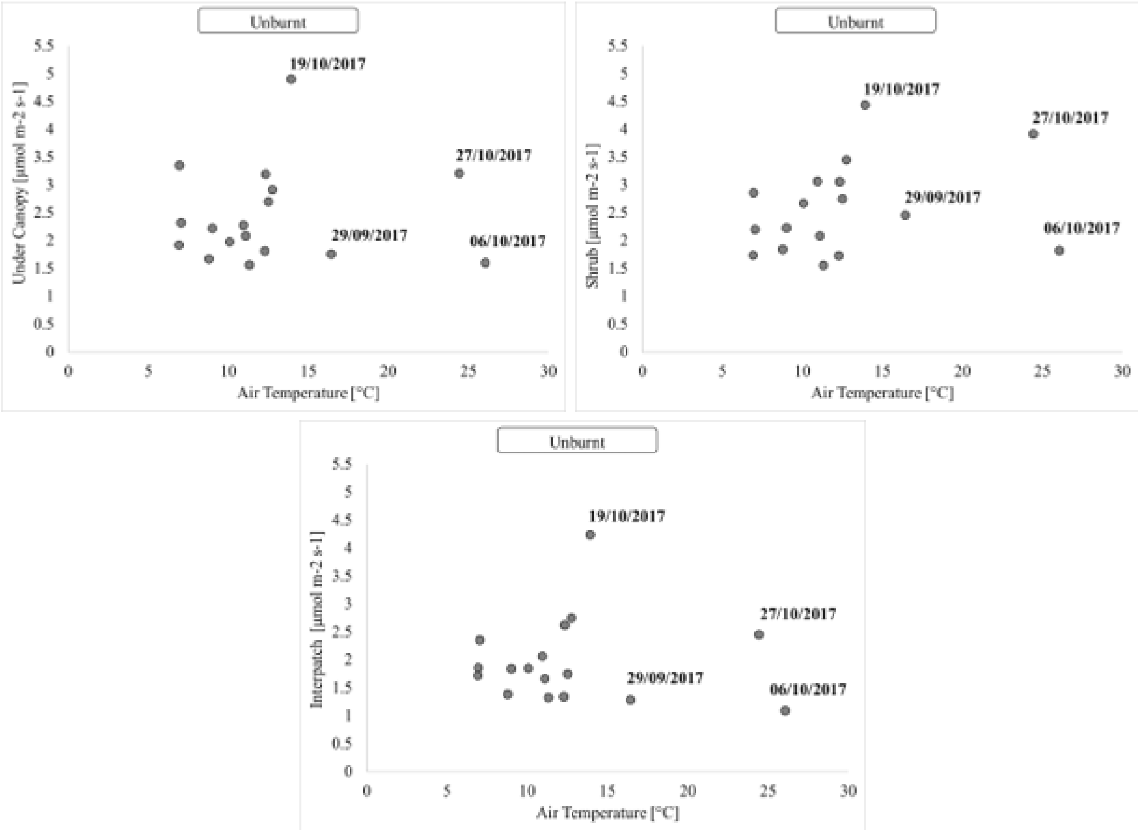

Figure 31: Soil respiration *versus* air temperature for the unburnt site.

2.4 Conclusions and future research

This study reveals the importance of assessing soil respiration rates by considering the role of wildfire and its effects on those rates *in situ*, regarding the wildfire occurrence, severity, time since fire, soil and weather conditions. Wildfire modified the study area in structure and composition of the original forest vegetation, affecting the physical, chemical and biological characteristics, which consequently affected soil respiration rates.

In this study, three specific objectives were established and through the results was possible to reach several conclusions for a better understanding of the effects of wildfires on soil respiration in a maritime pine plantation. Therefore, the main conclusions were:

- In the burnt site, the soil respiration rates were lower compared to the unburnt site, which proves that fire occurrence has severe consequences on soil. According with the results obtained it is possible to conclude that fire severity does not have major effects on soil respiration rates, since the values registered were very similar for moderate and high severity.

- The soil respiration rates presented higher values for the under canopy structural unit compared to the shrub and interpatch units. In contrast, the structural unit that registered lower values of soil respiration was the interpatch. The structural units that presented a strong correlation coefficient was: under canopy moderate severity with under canopy high severity; under canopy moderate severity with interpatch burnt and under canopy high severity with interpatch burnt.

- The fact that the period of study was only six months does not allow to make an accurate analysis of the evolution of soil respiration rates with time since fire. Also, due to the short study period, it is not possible to conclude if the soil is recovering since that happens in 3 to 10 years since the fire event. The soil temperature and air temperature showed higher values for the burnt site compared to the unburnt. However, for soil moisture occurred the opposite, i.e., higher values were recorded at the unburnt site compared to the burnt.

It is important to mention that the soil and weather conditions (soil temperature, soil moisture and air temperature) cause effects on soil respiration rates. However, these effects are not a result of each individual parameter but of its combined action, in accordance with the results obtained.

The different responses of soil respiration to all these parameters and conditions may shift with the years after the wildfire occurrence, which highlights the need to continue this study and assess C effluxes in Mediterranean forests. It is also important to better predict the impact that wildfires have on soil properties, in order to take actions to minimize those impacts. Therefore, it is very important to understand the temporal dynamics of soil respiration and the controlling factors.

References

Alcañiz, M., Outeiro, L., Francos, M., Úbeda, X., 2018. Effects of prescribed fires on soil properties: A review. Sci. Total Environ. 613–614, 944–957. https://doi.org/10.1016/j.scitotenv.2017.09.144

Badía, D., López-García, S., Martí, C., Ortíz-Perpiñá, O., Girona-García, A., Casanova-Gascón, J., 2017. Burn effects on soil properties associated to heat transfer under contrasting moisture content. Sci. Total Environ. 601–602, 1119–1128. https://doi.org/10.1016/j.scitotenv.2017.05.254

Campos, I., Abrantes, N., Keizer, J.J., Vale, C., Pereira, P., 2016. Major and trace elements in soils and ashes of eucalypt and pine forest plantations in Portugal following a wildfire. Sci. Total Environ. 572, 1363–1376. https://doi.org/10.1016/j.scitotenv.2016.01.190

Certini, G., Nocentini, C., Knicker, H., Arfaioli, P., Rumpel, C., 2011. Wildfire effects on soil organic matter quantity and quality in two fire-prone Mediterranean pine forests. Geoderma 167–168, 148–155. https://doi.org/10.1016/j.geoderma.2011.09.005

CLIMATE-DATA, 2018. Clima: Vila de Rei: Climograma, Temperatura e Tabela climática Vila de Rei - Climate-Data.org [WWW Document]. URL https://pt.climate-data.org/location/6939/ (accessed 7.4.18).

Curiel, Y.J., Janssens, I.A., Carrara, A., Meiresonne, L., Ceulemans, R., 2003. Interactive effects of temperature and precipitation on soil respiration in a temperate maritime pine forest. Tree Physiol. 23, 1263–1270.

Ferreira-Leite, F., Bento-Gonçalves, A., Vieira, A., Nunes, A., Lourenço, L., 2016. Incidence and recurrence of large forest fires in mainland Portugal. Nat. Hazards 84, 1035–1053. https://doi.org/10.1007/s11069-016-2474-y

Francos, M., Pereira, P., Mataix-Solera, J., Arcenegui, V., Alcañiz, M., Úbeda, X., 2018. How clear-cutting affects fire severity and soil properties in a Mediterranean ecosystem. J. Environ. Manage. 206, 625–632. https://doi.org/10.1016/j.jenvman.2017.11.011

Ghani, A., Dexter, M., Perrott, K.W., 2003. Hot-water extractable carbon in soils: A sensitive measurement for determining impacts of fertilisation, grazing and cultivation. Soil Biol. Biochem. 35, 1231–1243. https://doi.org/10.1016/S0038-0717(03)00186-X

Jiménez-González, M.A., De la Rosa, J.M., Jiménez-Morillo, N.T., Almendros, G., González-Pérez, J.A., Knicker, H., 2016. Post-fire recovery of soil organic matter in a Cambisol from typical Mediterranean forest in Southwestern Spain. Sci. Total Environ. 572, 1414–1421. https://doi.org/10.1016/j.scitotenv.2016.02.134

Köster, K., Köster, E., Orumaa, A., Parro, K., Jõgiste, K., Berninger, F., Pumpanen, J., Metslaid, M., 2016. How Time since Forest Fire Affects Stand Structure, Soil Physical-Chemical Properties and Soil CO2 Efflux in Hemiboreal Scots Pine Forest Fire Chronosequence? Forests 7, 201. https://doi.org/10.3390/f7090201

López-Serrano, F.R., Rubio, E., Dadi, T., Moya, D., Andrés-Abellán, M., García-Morote, F.A., Miettinen, H., Martínez-García, E., 2016. Influences of recovery from wildfire and thinning on soil respiration of a Mediterranean mixed forest. Sci. Total Environ. 573, 1217–1231. https://doi.org/10.1016/j.scitotenv.2016.03.242

Marañón-Jiménez, S., Castro, J., Kowalski, A.S., Serrano-Ortiz, P., Reverter, B.R., Sánchez-Cañete, E.P., Zamora, R., 2011. Post-fire soil respiration in relation to burnt wood management in a Mediterranean mountain ecosystem. For. Ecol. Manage. 261, 1436–1447. https://doi.org/10.1016/j.foreco.2011.01.030

Martín, A., Díaz-Raviña, M., Carballas, T., 2012. Short- and medium-term evolution of soil properties in Atlantic forest ecosystems affected by wildfires. L. Degrad. Dev. 23, 427–439. https://doi.org/10.1002/ldr.1078

Martínez-García, E., López-Serrano, F.R., Dadi, T., García-Morote, F.A., Andrés-Abellán, M., Pumpanen, J., Rubio, E., 2017. Medium-term dynamics of soil respiration in a Mediterranean mountain ecosystem: The effects of burn severity, post-fire burnt-wood management, and slope-aspect. Agric. For. Meteorol. 233, 195–208. https://doi.org/10.1016/j.agrformet.2016.11.192

Matteucci, M., Gruening, C., Goded Ballarin, I., Seufert, G., Cescatti, A., 2015. Components, drivers and temporal dynamics of ecosystem respiration in a Mediterranean pine forest. Soil Biol. Biochem. 88, 224–235. https://doi.org/10.1016/j.soilbio.2015.05.017

Mikita-Barbato, R.A., Kelly, J.J., Tate, R.L., 2015. Wildfire effects on the properties and microbial community structure of organic horizon soils in the New Jersey Pinelands. Soil Biol. Biochem. 86, 67–76. https://doi.org/10.1016/j.soilbio.2015.03.021

Morillas, L., Roales, J., Portillo-Estrada, M., Gallardo, A., 2017. Wetting-drying cycles influence on soil respiration in two Mediterranean ecosystems. Eur. J. Soil Biol. 82, 10–16. https://doi.org/10.1016/j.ejsobi.2017.07.002

Muñoz-Rojas, M., Lewandrowski, W., Erickson, T.E., Dixon, K.W., Merritt, D.J., 2016. Soil respiration dynamics in fire affected semi-arid ecosystems: Effects of vegetation type and environmental factors. Sci. Total Environ. 572, 1385–1394. https://doi.org/10.1016/j.scitotenv.2016.02.086

Paré, D., Banville, J.L., Garneau, M., Bergeron, Y., 2011. Soil Carbon Stocks and Soil Carbon Quality in the Upland Portion of a Boreal Landscape, James Bay, Quebec. Ecosystems 14, 533–546. https://doi.org/10.1007/s10021-011-9429-7

Pereira, P., Úbeda, X., Martin, D.A., 2012. Fire severity effects on ash chemical composition and water-extractable elements. Geoderma 191, 105–114. https://doi.org/10.1016/j.geoderma.2012.02.005

Poirier, V., Paré, D., Boiffin, J., Munson, A.D., 2014. Combined influence of fire and salvage logging on carbon and nitrogen storage in boreal forest soil profiles. For. Ecol. Manage. 326, 133–141. https://doi.org/10.1016/j.foreco.2014.04.021

Shakesby, R.A., Bento, C.P.M., Ferreira, C.S.S., Ferreira, A.J.D., Stoof, C.R., Urbanek, E., Walsh, R.P.D., 2015. Impacts of prescribed fire on soil loss and soil quality: An assessment based on an experimentally-burned catchment in central Portugal. Catena 128, 278–293. https://doi.org/10.1016/j.catena.2013.03.012

Smith, D.R., Kaduk, J.D., Balzter, H., Wooster, M.J., Mottram, G.N., Hartley, G., Lynham, T.J., Studens, J., Curry, J., Stocks, B.J., 2010. Soil surface CO2flux increases with successional time in a fire scar chronosequence of Canadian boreal jack pine forest. Biogeosciences 7, 1375–1381. https://doi.org/10.5194/bg-7-1375-2010

Treseder, K.K., Mack, M.C., Cross, A., Applications, S.E., Dec, N., 2012. Relationships among Fires , Fungi , and Soil Dynamics in Alaskan Boreal Forests RELATIONSHIPS AMONG FIRES , FUNGI , AND SOIL DYNAMICS IN ALASKAN BOREAL FORESTS 14, 1826–1838.

Uribe, C., Inclán, R., Sánchez, D.M., Clavero, M.A., Fernández, A.M., Morante, R., Cardeña, A., Blanco, A., Van Miegroet, H., 2013. Effect of wildfires on soil respiration in three typical Mediterranean forest ecosystems in Madrid, Spain. Plant Soil 369, 403–420. https://doi.org/10.1007/s11104-012-1576-x

Zavala, L.M., De Celis, R., Jordán, A., 2014. How wildfires affect soil properties. A brief review. Cuad. Investig. Geográfica 40, 311. https://doi.org/10.18172/cig.2522